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A TEXT-BOOK
OF
PHYSICS

FOR USE IN SECONDARY SCHOOLS

BY
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PREFACE

The student must expect to encounter many difficulties in any proper study of Physical Science.

The aim in this book is not to omit topics which have been found to be difficult, but to explain and illustrate them in such a way that the earnest student may readily comprehend them.

The difficulties which a student has in understanding a topic often lies in the method of statement or presentation rather than in the nature of the subject. An endeavor has been made in the preparation of this book to make language the minimum difficulty and to teach as much physics as possible.

The experiments described are in no sense intended as a series of laboratory exercises. No attempt has been made to describe even a full list of experiments needed in recitation. The text itself naturally suggests the experiments which an enthusiastic teacher is sure to make when possible. The experiments which are described are intended only as helps and suggestions where the text itself might not be sufficiently suggestive.

A separate course in laboratory exercises should be pursued and should follow close upon the discussion and study of topics in the text-book.

The problems are carefully selected with the purpose in view of making them a means of review and a test of thorough knowledge of the text. The problems in a book of physics of this grade should be a test of knowledge of physical principles rather than a test of mathematical ability. More good will result from a few problems which are thoroughly mastered than from a great number which can be only lightly touched upon.

The teacher cannot give too much attention to a *vigorous drill* on the principles announced in the text. Physics is not a subject for discussion and speculation. It consists of a number of scientific facts which are to be known and understood. These facts are learned (1) by a study of the text-book, (2) by recitation and conference in the class room, (3) by experiments both in the class room and in the laboratory, and (4) by the solution of problems.

During the recitation the teacher should give short, easy problems which may be solved mentally or by use of a few figures on paper. The thought must be constantly directed to the physical principles involved.

When a student reaches a list of problems in this book, he should be able to solve them without a great deal of difficulty. The facility with which he does the problem-work may be taken as an index of his knowledge of the physical principles.

No part of the work presented in this book is to be omitted. A student who is ready to do this class of work should take every paragraph as it comes. One year is sufficient time for the completion of this course.

J. A. C.

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PHYSICS

CHAPTER I.

MATTER AND ITS PROPERTIES.

1. Matter.

The science of physics is largely concerned with matter and the laws by which it is governed.

It is not possible at the present stage in the progress of science to give a fundamental definition of matter. We do not know what water, iron, air, and wood *are*. It is not necessary in the study of physical science that we *should* know, though such knowledge would be very desirable and valuable.

The properties of matter and the laws and forces by which matter is controlled are the important considerations in this science. Though we do not know what water *is*, we do know that if it is collected in a reservoir, it may be used in turning water-wheels, doing various kinds of work, and in supplying buildings, at a lower level, with water under pressure.

We may say that *matter is anything that occupies space.* This does not tell us what matter is, but for the present it may be given as a definition.

Most forms of matter can be seen, felt, or perceived in other ways, though some substances, such as air and other gases, are not readily perceived by the senses.

A limited portion of matter is called a *body.* A lake is a body of water.

Any one kind of matter is called a *substance*. Glass, wood, iron, and air are examples of substances.

2. The Constitution of Matter.

There are strong reasons for believing that matter is composed of a great number of very small particles called *molecules.*

All the molecules are in a quivering motion, the motion increasing when the body is warmed and decreasing when the body is cooled.

The molecules are not in permanent contact with each other. They may collide and rebound, but there are spaces between them in which the molecule may move.

Even such substances as steel, glass, and ice are to be considered as made up of molecules, almost countless in number, separated a very short distance from each other, and all in a quivering motion.

Several kinds of matter may be united in one molecule. A molecule of water, H_2O, is composed of hydrogen and oxygen. A molecule of sugar, $C_6H_{12}O_6$, contains carbon, hydrogen, and oxygen.

A body may be a solid, a liquid, or a gas, depending on the rapidity of the motion of its molecules. This is discussed more fully in the chapter on heat.

3. Parts of the Molecule.

There are also strong reasons for believing that molecules are composed of still smaller particles called *atoms.*

Atoms may combine in a variety of ways, forming the molecules of the various substances. Thus, two atoms of hydrogen unite with one of oxygen, forming water, H_2O. One atom of sodium combines with one of chlorine, forming common table salt, $NaCl$. Two atoms of hydrogen, one of sulphur, and four of oxygen, combine to form sulphuric acid, H_2SO_4.

The relations of atoms and the combinations which they make with each other form the chief subject of the science of *chemistry*.

The atom, in turn, is composed of still smaller particles called *electrons*. The electron is the smallest particle of which modern science has any knowledge.

A number of electrons unite to form the atom. Several atoms together form a molecule. A great number of molecules combine to form the various substances with which we are familiar.

Modern investigation into the nature of the electron gives promise of very important discoveries and may lead to a knowledge of what matter *is*.

4. Size of the Molecule.

We can never hope to see anything as small as a molecule, even when we look through the strongest microscopes. The smallest object we can possibly see with the naked eye is composed of many millions of molecules. It has been estimated that 43,000,000 molecules of hydrogen placed side by side in a straight line would form a row one inch long. The atom and the electron are, of course, still smaller.

5. The Electron.

The discovery of radium opened up a great field of investigation. Not only radium but also a number of other substances have been found to be radio-active, that is they emit light, heat, or some other form of energy into the surrounding space.

That which is of chief interest in reference to radium is the fact that this energy does not result from a rearrangement of the atoms of molecules, but from a breaking down of the atom itself. The atom is divisible. The very small particles which make up the atoms are often called *electrons*.

The electrons, in some intimate relation to the ether which fills all space, are probably the fundamental particles of which all matter is formed.

6. Properties of Matter.

Anything that belongs to matter by nature, is one of its *properties.* There are physical properties and chemical properties. We are here concerned only with the former.

Some properties of matter are *general,* that is, they belong to all kinds of matter at all times. Other properties are *special,* that is, they are found in some kinds of matter, but are wanting in others.

We give below a number of the most important properties.

7. Inertia.

A body of matter resists any attempt to change its state of rest or motion. This is a general property called *inertia.* The best test of matter is its inertia. Matter may be defined as, *anything that possesses inertia.*

We are compelled to deal with this common property of matter in every movement we make. It is a common experience that a heavy mass of matter cannot be quickly set in rapid motion, and when once in motion it cannot be easily or quickly stopped.

Fig. 1.

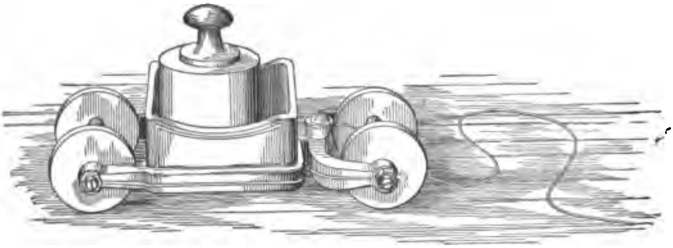


Illustration of inertia.

Experiment 1.

Attach a fine thread to a loaded cart as shown in Fig 1. By pulling gently on the string, the cart can easily be drawn along a level surface, and may be given any desired velocity. Slacken the string and give it a sudden jerk. The string will be broken without perceptibly moving the cart. The inertia of the mass of matter prevents any sudden change.

Experiment 2.

Suspend a heavy iron ball by a thread. Fasten another thread of the same kind to the hook beneath the ball. By pulling steadily downward on the lower thread, the upper one will break because it must bear the weight of the ball and also the pull.

By giving the lower thread a very sudden jerk downward, the lower thread will break and the ball will remain suspended. The inertia of the ball resists the attempt to suddenly set it in motion.

Experiment 3.

Place a coin on the end of a finger. Beneath the coin place one end of a strip of paper about two inches long. Wet a finger of the other hand and strike down upon the free end of the paper. The paper will be removed, but the coin will remain in place. The inertia of the coin prevented its sudden start.

Inertia does not mean inactivity. A cannon ball in flight possesses the same inertia as when at rest. A body of matter persists in doing whatever it *is* doing. This principle will be more fully discussed in a later chapter on the laws of motion.

FIG. 2

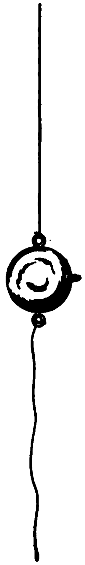


Illustration of inertia.

8. Extension.

A body of matter, however small, occupies space. It extends in three directions. That is, it has length, breadth, and thickness.

Measurement of extension is an important part of the work in physics. For this purpose, systems of units are employed. These are given in the next chapter.

9. Indestructibility.

Matter can neither be created nor destroyed by any change which we can make. Matter is constantly being changed, as when the tallow in a candle or the oil in a lamp burns away. They seem to be destroyed, but if all the gases which were formed during combustion were collected and weighed, the weight would be found to be the same as that of the material which entered into the combustion.

The food which we eat may be greatly changed. Some of it is stored in the body. The greater part of it is consumed and its waste products are constantly being given off in expiration, sweat, and so on, but the material of the food is never destroyed.

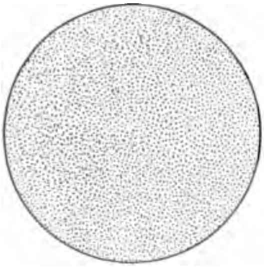
Whatever changes matter may undergo, the amount of it is a constant quantity.

10. Porosity.

All matter is porous in the sense, already explained, that it is composed of molecules which are separated from each other.

We say that a piece of pumice stone is porous because it is filled with small holes, but the term *porosity* is used in a different sense here. Iron, gold, and water, for example, do not completely fill the space which they seem to occupy.

FIG. 3.



Molecules magnified millions of times.

The spaces between the molecules are so exceedingly small that there is no way of actually observing them, but if a particle of matter could be sufficiently enlarged, the molecules and the spaces between them would have somewhat the appearance shown in Fig. 3.

The molecules of certain substances may pass in between those of other substances, and it is in this sense we can say that all matter is porous.

Experiment 4.

Fill a small test-tube a little more than half full of water. Tip the tube slightly to one side and fill the remainder of the tube with alcohol. Pour the alcohol in a fine stream, letting it run down the side of the tube, so as not to disturb the water.

Hold the thumb firmly upon the top of the tube, excluding all air. The tube now appears to be completely filled with liquid. By inverting it, the two liquids will be intimately mingled and a strong suction will be felt on the thumb. A space is now observed, between the liquid and the thumb, which is not occupied by the liquid. When the two liquids are mixed, they do not occupy as much space as when they are separate. Part of the molecules of one substance appear to move in between those of the other.

There are many illustrations of the porosity of even hard substances. Water may, under pressure, be forced through plates of iron. Zinc will absorb a considerable quantity of mercury without increasing in size. Gold, copper, and other metals will also absorb mercury.

11. Impenetrability.

Two bodies of matter cannot occupy the same space at the same time. This is the usual statement of the property of *impenetrability*. Generally speaking, it is true that a body of matter is excluded from space already occupied by other matter. Nearly all the bumps and bruises to which our bodies are subjected, result from this fact.

It is also a common experience that when a vessel is full of a liquid or a gas, other liquids or gases cannot be poured into the same vessel.

From what has just been said about the porosity of matter, however, we must infer that a body of matter is not completely impenetrable. A vessel may be full of potatoes, no more potatoes can then be put into that vessel, but a considerable quantity of wheat may be filled into the spaces between the potatoes. The vessel will then be more nearly filled with matter, but a considerable quantity of fine sand may still be filled into the spaces between the grains of wheat. Thus the basket of potatoes and the wheat may be said to be penetrable. In a similar manner, the water and alcohol, as described in the experiment above, are penetrable.

Only the smallest particle of matter, the electron, probably, can strictly be said to be impenetrable.

12. Elasticity.

A body that will regain its original shape when the force which changed its shape is removed, is said to be elastic. A bar of steel is elastic because when bent it will spring back as soon as the bending force is removed. The elasticity of the bow gives the motion to the arrow.

All substances are, to some extent, elastic, though some are so slightly so that substances may be classified as elastic and nonelastic.

A body is perfectly elastic when it will completely regain its original shape. Ivory is a very elastic substance, but a gas is perfectly elastic.

The degree of elasticity of a body is determined by the *completeness* with which it regains its original shape. The distance through which a body may be changed in shape and yet recover, is called the limit of its elasticity. Rubber has a large limit of elasticity, but ivory is more elastic.

13. Plasticity.

When the shape of a body is changed and remains so after the force which caused it is removed, the body is said to be plastic. Bodies which are nonelastic are plastic. Soft clay and putty are plastic. Lead is so slightly elastic that it is classed with the plastic substances.

14. Cohesion and Adhesion.

Cohesion is the attraction between the molecules of a substance. *Adhesion* is the attraction between separate bodies of substances. A drop of water will cling to the tip of the finger because the molecules of the water cling to each other (cohere), and also adhere to the finger.

Cohesion is a property of all solids and liquids, though it differs widely in different substances.

The property is most noticeable in solids and gives them firmness and rigidity.

The molecules of some of the metals cohere very strongly. A steel wire will support a heavy weight without breaking. Such a wire is said to have great *tenacity*, and the load which it will bear is the measure of its ***tensile strength.*** Steel wire has the greatest tensile strength, the next is iron wire, and, after it, copper.

Steel wires are stretched between the iron pins in a pianoforte, and the sounding board in a good instrument of that kind is made strong enough to resist a tension of thirty tons.

The cohesive force is exerted only through exceedingly minute distances. When a glass vessel, for example, is broken, the pieces cannot be put close enough together again to cause the molecules to cohere. If, however, two pieces of glass be heated till they become plastic, and then are pressed together, the cohesion between the molecules at the edges of the two pieces may be made as strong as before they were broken apart. The blacksmith takes advantage of this principle in welding together two pieces of iron.

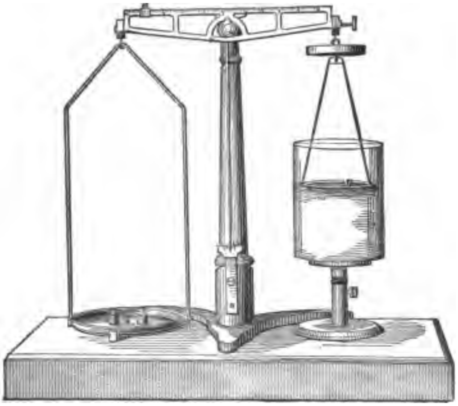
The cohesive force in liquids is not always so apparent as in solids. A portion of a liquid, however, cannot be separated from the remainder without the use of some force. This is not so apparent when a small quantity of a liquid is dipped from a vessel, but when the attempt is made to lift a broad board straight up from the surface of water, considerable effort is found to be necessary.

By use of the spring scales or, better, the balance as arranged in the experiment below, the force of cohesion per unit area may be determined.

Experiment 5.

Suspend from one end of the beam of a balance a disk of any convenient size and material. The disk must be perfectly clean on its lower surface and must hang in a horizontal position. Balance the beam and then raise a vessel of water to the under surface of the disk. Now place weights in the scale pan at the other end of the beam until the disk is just pulled away from the water. Note the area of the disk and the value of the weights. From these, calculate the cohesion of water per unit area.

FIG. 4.



Cohesion.

In an experiment, the apparatus for which is shown in Fig. 4, a disk three inches in diameter was used. The area of water affected would then be nearly seven square inches. The weight needed to overcome the cohesion was nearly one ounce. Hence the cohesion per square inch was about $\frac{1}{7}$ ounce.

It is seen in experiments like the one just described, that the lower surface of the disk is wet when it is pulled away from the water. The disk was not separated from the water, but the water itself was pulled asunder. The adhesion between the disk and the water, was stronger than the cohesion of the water. This is always true of liquids which wet solids.

The hand may be plunged into mercury and taken out clean and dry. This is not because there is no adhesion between the hand and mercury, but because the cohesion within the liquid is greater than the adhesion to the hand.

15. Hardness.

The hardness of a substance is tested by its ability to scratch or wear away other substances. This property probably results from the arrangement of the molecules within the substance. The diamond is the hardest substance. The next is carborundum, which is made in large quantities at Niagara Falls by melting together coke and sand in an electric furnace. Carborundum is extensively used as an abrasive. It is made up in form of disks, like emery wheels, and used to grind and smooth other solids. Solids differ in hardness all the way from the diamond down to those which may easily be scratched with the finger nail.

Steel may, within certain limits, be made to take any degree of hardness by a process of heating and cooling. If it is raised to a high temperature and suddenly cooled by immersion in water or oil, it will be very hard and brittle. If the steel is to be used for tools, it must be hard enough to resist strong blows and to hold a sharp edge, and yet must not be so hard that it will easily break. The process of securing the desired hardness is called *tempering*. This is done by heating the steel to just the proper temperature and then suddenly cooling it.

When steel is highly heated and then slowly cooled, it will be soft and tough. This process is called *annealing*.

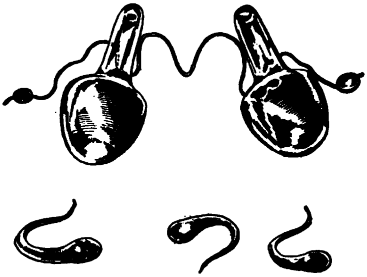
Glassware is annealed by being passed slowly through a long oven which is very hot at one end and gradually decreases in temperature to the other end. The trip through the oven may require several days. Glass treated in this way is much less liable to break.

Experiment 6.

A Boulognese flask is made of heavy, unannealed glass. It has the form shown in the upper part of Fig. 5. The bottom of the flask is very thick and, apparently very strong. The glass was rapidly cooled and so is under a severe strain which makes it very brittle.

As long as the glaze on the surface is unbroken, the flask will remain intact; but the slightest scratch will cause the flask to break into many pieces. A bullet or a lead pencil may be repeatedly dropped into the flask without breaking it, but a light crystal of carborundum or quartz dropped into it, will make a very slight scratch on the bottom and thus a crack is started which continues until the glass is shattered in many pieces.

Fig. 5.



Boulognese flasks and Prince Rupert's drops.

Prince Rupert's drops, shown in the lower part of the figure, are made in a similar way. Break the point off the end and the whole will break into pieces as fine as table salt.

16. Malleability and Ductility.

Some metals can be hammered or rolled into very thin sheets or can be drawn out into very fine wires. The former property is called *malleability* and the latter, *ductility*. All solid metals possess these properties to some degree, but only a few are remarkable on this account. Gold is the most malleable metal. It can be hammered into leaves so thin that it would require one million of them to make a book one inch thick. Platinum is the most ductile of metals. It can be drawn into wire so fine that a single strand of it can scarcely be seen with the naked eye. The mineral quartz is also very ductile when heated to a plastic condition. Quartz fibres can be spun so fine that they cannot be seen even by aid of a good microscope.

Experiment 7.

Heat a glass rod or tube in a Bunsen or alcohol flame till the glass is quite soft at one point. Remove the glass from the flame and quickly separate the two ends of the rod, or tube, as far as the arms will reach. A fine thread of glass will extend from one piece to the other.

17. Crystallization.

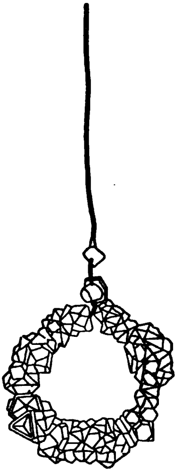
Most substances, on changing from a liquid into a solid state, will crystallize. Substances which do not crystallize, such as glass and rosin, are said to be *amorphous*, that is, without a definite crystalline form.

That crystals may form, it is necessary that the molecules be free to arrange themselves in a definite order. This condition is secured when a substance is dissolved or melted.

Experiment 8.

Dissolve 200 grams of alum in 200 cubic centimeters of water. Boil the water till all the alum is dissolved. Set the solution aside and suspend in it any design made of cotton-covered copper wire, No. 30. In the course of a few hours, as the solution slowly cools, crystals will form on the cotton covering of the wire, as shown in Fig. 6.

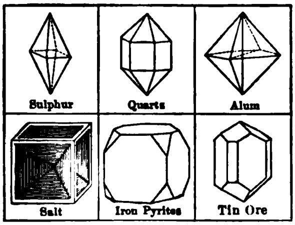
FIG. 6.



Alum crystals.

If the numerous crystals which adhere to the wire in the experiment above, be closely examined, it will be found that all are formed after one pattern. By selecting the ones which are least crowded by others, the perfect alum crystal is seen to have the shape of an octohedron, as shown in Fig 7.

FIG. 7.



Forms of crystals.

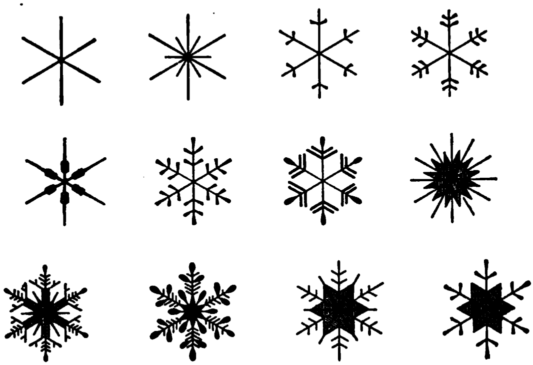
Numerous substances in the crystalline form may be found on the shelves of a drug store or in a chemical laboratory.

The principle is utilized in the manufacture of sugar, rock candy, salt, and numerous other articles.

In nature, on all sides, crystalline forms may be observed. When water is frozen, it is converted into crystals of ice. If the water is in the form of vapor in the air, it will, when frozen, collect into most beautiful hexagonal forms and fall to the earth as snow flakes.

All snow flakes have the same general form, but the variety is infinite. A few forms are shown in Fig. 8. Others may readily be examined by collecting flakes, as they fall, upon a piece of ice-cold glass or cloth.

FIG. 8.

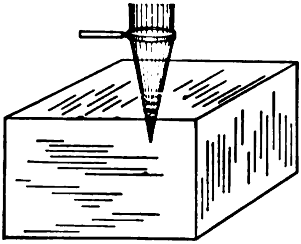


Snow flakes.

The frost patterns often seen on windows in the winter time consist of ice crystals which are slowly built up by the water vapor collected from the air in the room and frozen by the cold window pane.

When water freezes, the crystals are so crowded together that they appear as one solid block. Even here, the crystalline structure may be made apparent by melting some of the ice on the interior of a clear block. This may be done by use of a reading or burning glass. The sun's rays are brought to a focus within the block of ice and so the water will be rapidly melted there and crystals will project in all directions from the sides of the cavity.

Fig. 9.



For showing the crystalline structure of ice.

Many of the metals have a crystalline structure. When they are melted the crystals are destroyed, but, on solidifying, they return to the crystalline form. Cast iron is a good example. A freshly broken piece of such iron plainly shows the crystals. The effect of crystallization on the size and strength of materials will be treated in a later chapter.

18. Ether.

Ordinary matter, such as that of which we have just been speaking, is made known to us through our senses, chiefly the sense of feeling. But there is another substance, called *ether*, which we cannot know by any of our senses. The evidence that ether exists is wholly indirect, but the proof of its existence is quite conclusive.

It is assumed that all space is filled with ether and that all ordinary matter is imbedded in it. We have shown that all matter is porous. The spaces between the molecules are all filled with ether. The molecules of matter are bathed in the ether. All the air may be pumped out of a vessel, but the vessel is still full of ether. It is not possible to pump out the ether because the hardest matter that we know would let the ether pass through it with greater freedom than water will pass through a coarse sieve.

The whole space between the earth and the sun and stars is filled with ether. It has been proven that light is a wave motion. Waves can travel only on some medium such as water or air. When a wave of light comes from the sun to the earth, there must be some medium upon which it may travel. This is the ether.

It is also proven that it requires about eight minutes for light to make the trip from the sun to the earth. The fact that it requires time, shows that the ether possesses inertia, which, we have shown, is one of the characteristic properties of matter.

Since waves can travel only in an elastic medium, it can also be inferred that the ether is elastic.

While ether is not matter in the ordinary sense, yet it possesses several of the important properties of matter and is a substance which actually exists, though beyond the ability of our senses to perceive it.

CHAPTER II.

UNITS OF MEASUREMENT.

19. Necessity of Units.

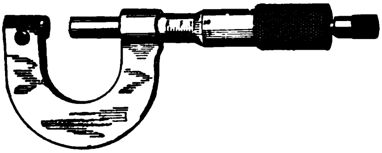
A unit, as here used, is *one* of any standard by which things are measured. The centimeter is a unit of length, the gram is a unit of mass, and a second is a unit of time. The question *how much* must be constantly answered in science as well as in the ordinary affairs of life. If you were to answer this question by simply giving a pure number, as 5 or 20, no one would know what was meant. By naming the unit, as 5 grams or 20 pounds, the answer becomes intelligible to all who know the value of the unit used.

It is plainly desirable that as many people of the civilized world as possible should use the same units and that all should be familiar with these units.

20. Necessity of Exact Standards.

Science has made rapid progress since the time when the scientist was able to make exact measurements. Very small differences in length, or mass, or time, are often very significant and can not be neglected. For this purpose it is necessary that the standards be exactly defined so that they may be kept the same at all times.

FIG. 10.



Micrometer screw.

It is necessary also that delicate instruments be provided for measurement of very small fractions of any given standard. The micrometer, shown in Fig. 10, will measure accurately a difference of one thousandth of a centimeter in length. Other instruments are made to measure differences of one ten-thousandth, one hundred-thousandth or less.

Delicate balances easily detect a difference in mass of one ten-thousandth of a gram.

By use of pendulums, two periods of time of exactly equal duration may be determined, or differences of one thousandth of a second may be detected and measured.

21. The Metric System.

The metric system is a system of units which was first adopted by the French government in the year 1799 A.D. It had its origin in a commission of representatives from ten different nations who met in France in the same year and established the precise length of the meter, and the mass of the kilogram.

After the units of length and mass were once fixed, the whole system was built up on a decimal ratio, that is, each unit of the system was found by multiplying the standard by 10 or some power of 10.

The simplicity of the system and the fact that it belonged to no particular nation, at once made it popular. Within a century after the date named above, it became the legal system of more than two-thirds of the civilized world, and in scientific work its use has become universal.

22. The Meter.

The standard international meter is a bar of platinum which contains 10 per cent of iridium. This alloy forms a very durable metal.

Near each end of the bar is a fine cross line. The distance between the two lines, when the temperature is 0°C., is called the meter and is marked M. Thirty-one of these bars were made. They are called the International Prototype Meters and are carefully guarded in the vault at the International Bureau of Weights and Measures near Paris.

Exact copies of these bars, called National Prototypes, were made and sent out to the countries which contribute to the International Bureau—two bars to each. The two sent to United States are in the custody of the Bureau of Standards at Washington, D. C.

The meter was adopted as the fundamental standard of length in United States in the year 1893 A. D.

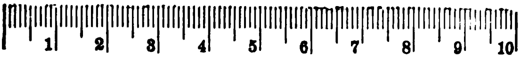
The yard, which was formerly the standard, is defined in terms of the meter, as $\frac{3600}{3937}$ meter, or the meter equals 39.37 inches.

NOTE.—An effort was made to have the meter equal to one ten-millionth of the distance from the equator to the north pole as measured on the meridian passing through Paris. It has since been found that this distance is 10,000,880 meters instead of 10,000,000 as intended.

Table of Metric Units of Length.

1 meter (m.) = the standard
$\frac{1}{10}$ meter = 1 decimeter (dm.).
$\frac{1}{10}$ decimeter ($\frac{1}{100}$ meter) = 1 centimeter (cm.).
$\frac{1}{10}$ centimeter ($\frac{1}{1000}$ meter) = 1 millimeter (mm.).

FIG. 11.



Scale, 1 decimeter, 10 centimeters, or 100 millimeters long.

10 meters = 1 dekameter (dkm.).
10 dekameters (100 meters) = 1 hektometer (hm.).
10 hektometers (1000 meters) = 1 kilometer (km.).

The centimeter and millimeter are the common units employed in the physical laboratory, where only short distances, as a rule, are measured. The meter would be used to get the dimensions of a room, and thus it is similar in its use to the yard in the English system. The kilometer is used to express distances which would be given in miles in the English system.

In addition to the units named in the table, the one-thousandth of a millimeter is frequently used to measure very small spaces, such as the width of a fine line. This unit is called the *micron* and is marked, μ. The one-thousandth of a micron is marked, $\mu\mu$.

23. Measurement of Area and Volume.

Since the area of any surface is the product of its two dimensions, and the volume is the product of three dimensions, it is not necessary that there be separate tables for area and volume. If a rectangle measures 12 cm. one way and 20 cm. the other, the area is 240 square centimeters (sq. cm.). A cube which measures 5 cm. along each edge, has a volume of 125 cubic centimeters (c.c.).

The capacity of a vessel, however, is measured not only in the cube of the unit of length but also in terms of another standard called the *liter*. The liter contains 1000 cubic centimeters. The parts of the liter are similar to the parts of the meter in the table of length.

Liter Table.

1 liter (l.) = the standard of capacity.
$\frac{1}{10}$ liter = 1 deciliter (dl.).
$\frac{1}{10}$ deciliter ($\frac{1}{100}$ liter) = 1 centiliter (cl.).
$\frac{1}{10}$ centiliter ($\frac{1}{1000}$ liter) = 1 milliliter (ml.).
10 liters = 1 dekaliter (dkl.).
10 dekaliters (100 liters) = 1 hectoliter (hl.).
10 hectoliters (1000 liters) = 1 kiloliter (kl.).

24. The Kilogram.

It is necessary that there should be a standard unit of mass as well as of length. At the same time that the length of the meter was established, a standard mass called the *kilogram* was also established. The International Kilogram is a mass of platinum alloyed with ten per cent of iridium. The same care was taken in its preparation and preservation as in case of the meter.

NOTE.—It was originally intended that the kilogram should have the same mass as that of 1000 cubic centimeters of pure water at 4° C. It has been found that this relation is very nearly, but not quite, exact.

Metric Table of Mass.

1 kilogram (kg.) = the standard of mass.
$\frac{1}{1000}$ kilogram = 1 gram (g.) = the unit of mass.
$\frac{1}{10}$ gram = 1 decigram (dg.).
$\frac{1}{10}$ decigram ($\frac{1}{100}$ gram) = 1 centigram (cg.).
$\frac{1}{10}$ centigram ($\frac{1}{1000}$ gram) = 1 milligram (mg.).
10 grams = 1 dekagram (dkg.).
10 dekagrams (100 grams) = 1 hektogram (hg.).
10 hektograms (1000 grams) = 1 kilogram (kg.).
1000 kilograms = 1 metric ton.

Thus the whole metric system is founded on the two fundamental standards—the *meter* and the *kilogram.* The value of all other units of the system is derived from these.

The relation between mass and volume is such that a cubic centimeter (c.c.) of pure water at 0° C., weighs almost exactly one gram. This, as we shall see, is a great convenience in many of the computations in physics.

25. The C. G. S. System.

The units of length, mass, and time, which are commonly used in science, are the *centimeter*, *gram*, and *second.* The first letters of these three words give name to this system. These units are largely employed throughout this book.

26. The English System.

While the metric system has been legalized in the United States, its use has not yet been made compulsory as in France, Germany, Italy, and a number of other nations.

We have in common use a system of weights and measures known as the English system. In it the fundamental standards are the *yard* and the *pound.*

27. The Yard.

The standard yard is defined as the distance between the centers of the transverse lines in the two gold plugs in a bronze bar at a temperature of 62° F. This bar is carefully preserved in the Standards Office at Westminster, London.

The yard is divided into thirty-six equal parts, called inches.

28. The Pound.

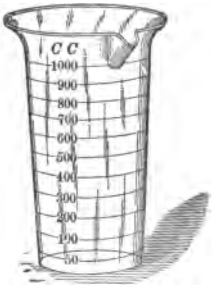
The standard pound is defined as a mass of platinum called the Imperial Avoirdupois Pound. One sixteenth of this mass equals one ounce, and one seven-thousandth of it equals one grain.

One avoirdupois pound equals nearly 453.6 grams.

29. The Two Systems.

One great convenience of the metric system is that it is a decimal system. The steps from any denomination to a higher or lower one are made by multiplying or dividing by ten or some power of ten. Thus, 26.342 kg. are at once reduced to grams by moving the decimal point three places to the right, that is, by multiplying by 1000. Also, 248 cm. may be at once reduced to meters by placing a point between the 2 and the 4, because there are 100 cm. in one meter.

Fig. 12.



Metric graduate.

There is also a great advantage in the fact that it is easy to pass from denominations of mass to those of volume. Since one cubic centimeter of pure water weighs one gram, 245 g. of water would fill a space of 245 c.c. Beakers which are graduated in cubic centimeters, also indicate the number of grams if the liquid is water. If the liquid measured were sulphuric acid, which is 1.84 times as heavy as the same bulk of water, then 100 c.c. of it would weigh 184 g.

The English system, on the other hand, has been a gradual development and so has not been formulated into a convenient system with all parts related in a simple manner as in the metric system. One thirty-sixth of a yard equals one inch. The rod contains 16½ feet. There are 16 ounces in the avoirdupois pound and 12 ounces in the

Troy pound. One gallon equals 231 cubic inches. One cubic foot of water weighs 62.42 pounds. Thus the system is without a regular graduation from one denomination to another and its use is the cause of a great deal of labor and confusion which is avoided by the use of the metric system.

A sudden change to the metric system would cause great inconvenience to many classes of merchants and manufacturers, and would cause considerable financial loss to some. For some time to come it will be necessary to learn both systems.

A number of the most important equivalents of the two systems are given in the Appendix I of this book.

Exercise in the Use of the Units described.

1. Reduce 2 meters to decimeters. To centimeters. To kilometers. To dekameters.

2. How many inches in 2½ meters? How many millimeters?

3. Reduce 1 km. and 12 cm. to millimeters.

4. Find the area of a page of this book in square centimeters, making use of a paper scale copied from page 19.

5. How many c.c. in 1 liter? In one centiliter? In 1 hektoliter?

6. In 1 dekagram and 1 decigram, how many grams?

7. Reduce 246.3 cg. to mg.

8. Reduce 47 inches to cm.

9. How many feet in 6 m.?

10. How many miles in 161 km.?

11. Reduce 20 liters to pints.

12. How many grains does 1 liter of water weigh?

13. Reduce 20 kg. to pounds.

14. How many grams in 100 ounces avoirdupois?

15. How many grams in 1543 grains?

16. Estimate your height in centimeters. Calculate and compare result with your estimate.

17. Calculate the number of square centimeters in a square foot.

18. The distance between two towns is 20 miles; what would be the proper designation of this distance in the metric system?

19. If you wished to order 11 pounds of sugar in terms of the metric system, for what should you ask?

20. What would be the cost of 10 meters of cloth at 50 cents per yard?

CHAPTER III.

MECHANICS.

FORCE.

30. Mechanics.

Mechanics is that branch of physical science which deals with force and its effect upon matter.

Under this head, then, is discussed the subject of *force* and the methods by which it is measured ; *motion* and the laws by which it is governed ; *work* accomplished by the expenditure of *energy ; machines ;* and the phenomena of *liquids* and *gases* when under stress.

31. Force.

Force is that which produces or tends to produce motion in bodies of matter. When one pushes or pulls against any resistance, he is exerting force. This force may or may not produce motion, but whenever the resistance is less than the force, motion will result. Force is exerted by a horse in pulling a carriage up a hill, and again in preventing the rapid descent of the carriage in going down the hill. A wind exerts force against any obstacle in its path. Steam exerts force against the piston head of an engine.

Force can be exerted only when there is some resistance to be overcome. It would not be possible to push or pull upon an object which would offer no resistance.

This mutual action between the force and the resistance is called a *stress.* The change of shape resulting from the stress is called the *strain.* Thus, as shown in Fig. 13, a coiled spring is acted upon by a weight W which is the force, and the support S which is the resistance. The spring is under a stress, and consequently, is strained.

32. How Force is Measured.

There are two methods of measuring force, one the *absolute* and the other the *gravitational* method. Force, by the former method, is determined by the speed which it imparts to a given mass in a given time. When force is employed to move a car along a smooth track, the more heavily the car is loaded, the greater is the force required to produce any desired speed. Also, the longer the force is applied, the greater will be the speed of the car; that is, the car will move faster and faster every second as long as the force acts upon it. This rate of increase is called the *acceleration* of a moving body.

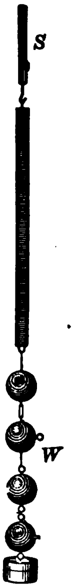
Thus the *force* is dependent on the *mass* that is moved and the *acceleration* that is produced. This may be expressed by the equation.

$$F = ma,$$

where F represents the force; m, the mass; and a, the acceleration.

Force, by the gravitational method, is measured by the earth-pull—the force of gravity. This is not an absolute method, because gravity is not the same at all points on the earth's surface, or at different distances from the center of the earth.

FIG. 13.



Stress and strain.

33. Units with which Force is Measured.

There are two absolute units of force, called the *dyne* and the *poundal*. The gravitational units are the *gram*, or *kilogram*, and the *pound*.

A dyne is a force which will give to one gram of matter an acceleration of one centimeter per second.

Thus if a mass of 5 g. is found to increase its speed 10 cm. every second, it must be acted on by a force of 50 dynes, for $F = ma = 5 \times 10$.

A poundal is a force which will give to one pound of matter an acceleration of one foot per second.

Thus if a mass of 10 pounds is known to increase in speed 32.2 feet each second, then from $F = ma$, F must be equal to $10 \times 32.2 = 322$ poundals.

One poundal is equal to 13,825 dynes, so that poundals may at any time be reduced to dynes by multiplying by this number, and dynes to poundals by dividing by the number.

Not only can the force be found when the mass and acceleration are given, but if any two of the three terms in the formula are given, the other one can easily be calculated.

Thus, if a force of 100 dynes acts on a mass of 4 g., we have, from $F = ma$, $100 = 4a$. From which $a = 25$ cm. per sec.

In the same manner, if a force of 20 poundals gives to a certain mass an acceleration of 5 feet per second, an easy calculation shows that the mass must be 4 pounds.

The gravitational units of force are determined by the pull of the earth upon certain masses of matter called the gram and kilogram in the metric system, or the pound in the English system.

The force of the earth-pull is exactly proportional to the amount of matter. If one body contains ten times as much matter as another, the earth will pull upon it with ten times greater force.

To lift a mass called one pound, then, requires the application of a certain force which is taken as one of the standards of force and called one pound. To lift a mass ten times as great would require a force of ten pounds.

Likewise the gram and the kilogram are units of force as well as units of mass.

These gravitational units of force are by no means used only in measuring the force of gravity. A force of twenty pounds may be used in pushing a cart along a level street, and this means that the force is as great as would have been used in lifting a mass of twenty pounds.

34. Comparison of the Two Systems.

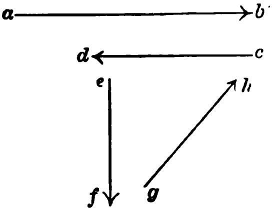
In the absolute units the force is equal to the product of the mass times the acceleration, while in the gravitational units the force is equal to the attraction of the earth on a certain mass of matter.

Now, if one gram of matter is allowed to fall freely toward the earth, it will have an acceleration of about 980 cm. per second. One dyne would give it an acceleration of only 1 cm. per second. Consequently a force of 1 *g. is equal to* 980 *dynes.* A force of 1 kg. then would be equal to 980,000 dynes.

The force of gravity would give to one pound of matter an acceleration of 32.2 feet per second, while a poundal would produce an acceleration of only 1 foot per second. Consequently here are 32.2 poundals in a pound. So, to reduce grams of force to dynes, multiply by 980. To reduce dynes to grams, divide by 980. To reduce pounds of force to poundals, multiply by 32.2. To reduce poundals to pounds divide by 32.2.

The acceleration due to the force of gravity is not the same on all parts of the earth's surface. In some places the force of gravity is greater than at others, and so the acceleration would be greater than 980 cm., or 32.2 feet; in other places, less than these numbers (see Table III in Appendix). For this reason the value of the gravitational units will be different in different localities.

FIG. 14.



Vector lines.

35. Vectors.

A vector is a directed quantity which may be represented by a straight line. The line represents both a magnitude and a direction. Arrow-heads are usually placed upon the lines to indicate the direction, and the unit of length may be taken to represent any magnitude desired, as, in vectors of force, each centimeter may represent a force of 100 dynes, or each inch may represent 50 or 100 dynes, or each inch may represent 50 or 100 pounds. Suppose that each centimeter represents 100 dynes, then *ab*, in Fig. 14, being 4 cm. long, represents 400 dynes acting at *a* and directed to *b*, while *cd*, being 3 cm. long, represents 300 dynes acting at *c* and directed to *d*. In a similar manner, *ef* and *gh* are representations of forces.

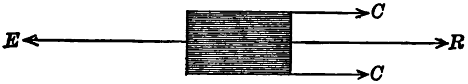
Any force may be completely represented by a line.

36. Resultant and Equilibrant.

A *resultant* force is one which may be substituted in place of two or more other forces, and which, alone, will produce the same effect as the others combined. The forces for which the resultant is substituted are then called the *components*.

For example, two horses pulling a wagon along a road would be a case of two parallel forces. If, now, in place of these two, a horse that can pull as much as the other two together be hitched to the front end of the wagon pole, the effect on the wagon would not be changed. The force exerted by the one horse would be a resultant of the other two for which it was substituted.

FIG. 15.



Resultant and equilibrant.

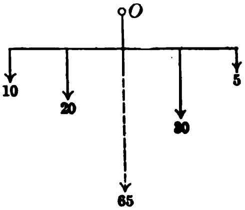
An *equilibrant* is a force exactly equal to the resultant and in the same line, but opposite in direction. Using the same example as above, if the one horse be hitched to the rear of the wagon and be made to pull with the same force as before, but in an opposite direction, the sum of the forces of the two horses will be balanced and the wagon will not be moved. This force is called the equilibrant because it produces equilibrium.

These various forces may be represented by vector lines as shown in Fig. 15. Suppose each centimeter of the length of the lines represents 50 kg. Then if the two components *C* and *C* are each 3 cm. long, they will represent 150 kg. each. The resultant, then, which is to be substituted for the components will be 300 kg., and the line which represents it must be 6 cm. long and in the same direction. The equilibrant, which must just balance the resultant, will also be represented by a line, *E*, 6 cm. long but in an opposite direction. *E* and *R* will lie in the same straight line.

37. Resultant of Parallel Forces.

When the forces are parallel and in the same direction, the resultant is the sum of all the components.

FIG. 16.



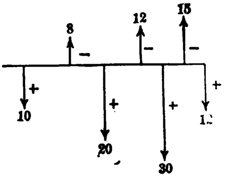
Parallel forces.

Thus, if weights, 10, 20, 30, and 5 pounds are suspended from the support, *O*, as in Fig. 16, they will have the same effect as if 65 pounds were hung from the same support.

When, however, the parallel forces are not all in the same direction, those in one direction may be considered positive (+) and in the other, negative (—). A general rule, applicable to all parallel forces may then be applied, as follows:

The resultant of any number of parallel forces is equal to the algebraic sum of the components.

FIG. 17.

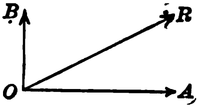


Parallel forces.

Thus, in Fig. 17, suppose all the downward forces to be positive, and those in the opposite direction, negative. The numbers in the figure indicate the forces in pounds. Then there are 72 pounds downward, and 35 pounds upward. The sum of +72 and —35 equals +37. That is, the resultant of all would be 37 pounds downward.

38. The Resultant of Forces that are not Parallel.

Fig. 18.



Resultant.

Two or more forces may be applied at one point and be exerted in different directions. For example, the vector line OA represents a force applied at O and directed toward A. OB is the vector line of another force applied at the same point and in a direction at right angles to the first. The resultant vector will plainly be represented by a line starting at O and lying between OA and OB. Since OA is a larger force than OB, as the lengths of the lines show, the resultant OR will lie more nearly in the direction OA than in that of OB. The line OR will represent, in magnitude and direction, a force which will produce the same result as the other two forces together.

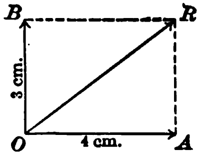
39. Parallelogram of Forces.

When two forces act upon a point in different directions, the vector lines of these forces may be considered the sides of a parallelogram, and the resultant will then be represented by a line drawn from the common point to the opposite angle of the parallelogram.

In Fig. 19, let OA and OB be the vector lines of two forces at right angles. The parallelogram constructed on these two lines is $OARB$. The resultant vector will then be OR. OA in the figure is 4 cm. long, and OB, 3 cm. From this it is easy to calculate that OR is 5 cm. in length.

Let each centimeter represent 50 dynes of force, then the resultant of 200 dynes along OA and 150 dynes along OB will be 250 dynes along OR.

Fig. 19.

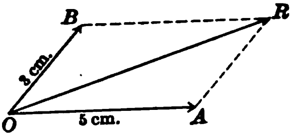


Parallelogram of forces.

When the forces act at right angles, the resultant can always be calculated in this manner.

When the forces do not act at right angles, the resultant may be found by completing the parallelogram on the given vector lines, drawing the diagonal which is the resultant, and measuring the resultant in the same units used for the components. In Fig. 20, *OA* and *O B* are inclined to each other at an angle of 60°. *OA* is 5 cm long, and *OB* 3 cm. By measurement with a ruler, *OR* is found to be 6.44 cm. long. If the two components are drawn on a scale of 100 dynes to the centimeter, each centimeter of the resultant vector line also represents 100 dynes. The resultant, therefore, is 644 dynes. This is known as the *graphical* method.

FIG. 20.



Graphical method.

Experiment 9.

Fasten a cord about 20 cm. long to the hooks of each of three spring scales, and fasten the other ends of the strings to a ring, *o*, Fig. 21. Lay the scales, face up, on a sheet of white paper. Fasten the rings of *a* and *b*, and pull upon *c* in any direction. Fasten *c*. All the cords are now under tension, the amount of which for each cord can be read on the scales. The ring is in equilibrium under the three forces acting upon it. Place the edge of a ruler beneath each cord and draw a straight line on the paper. Note the reading of each spring balance. After removing the balances the lines should be ex-

FIG. 21A.

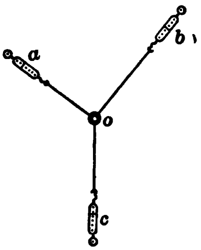
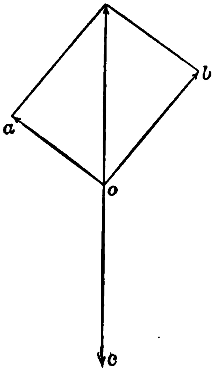


FIG. 21B.



Parallelogram of forces.

tended till they meet at a point in the center. Now, lay off on each line, measuring from the center outward, as many centimeters as there were units of force shown by the spring balances. Say, 1 cm. for every 10 g. It may be 1 cm. or 1 inch for every pound or ounce. Any convenient scale may be chosen, but all the lines must be treated alike.

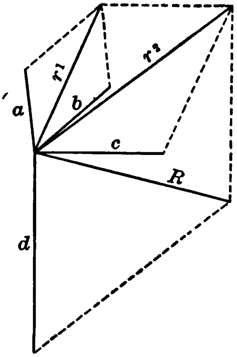
In the experiment illustrated in Fig. 21, each centimeter in Fig. 21B is taken to represent 10 g. The balance *a* showed a force of 30 g., hence *ao*, in Fig. 21B is made 3 cm. long and parallel to the cord *ao* in Fig. 21A. *b* showed a force of 40 g., so *ob* is made 4 cm. long, and parallel to the cord *ob*. A parallelogram is now completed on *oa* and *ob* as two of its sides, and the resultant *oR* is drawn. By measuring the length of *oR* and calling each centimeter 10 g., it is found that the resultant of *oa* and *ob* is just equal to the third force, *c*, and its line *oR* is in a straight line with *oc*, but in an opposite direction. Thus *oR* is the resultant, and *oc* is the equilibrant of the two forces *oa* and *ob*.

In a similar manner, a resultant may be found for any two of the forces, and the remaining force will then be found to just balance this resultant.

40. To Find the Resultant of any Number of Forces that are not Parallel.

When a number of forces are represented by vector lines, as *a*, *b*, *c*, and *d*, Fig. 22, the principle of the parallelogram of forces can be used to find the resultant of all. Thus the resultant of *a* and *b* is r^1. Then taking r^1 and *c* as the two sides of a parallelogram, r^2 is the resultant, and r^2 and *d* have a resultant *R*. Hence *R* is the resultant of all the forces. It is plain that this method may be applied to an indefinite number of forces of this kind.

FIG. 22.



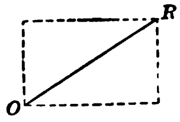
Resultant of several forces.

41. Composition and Resolution of Forces.

The processes just described of uniting a number of forces into one is called the *composition* of forces.

The process of separating one force into a number of component forces is called the *resolution* of forces. Thus, let *OR*, Fig. 23, represent a force. Suppose it is desired to resolve it into two forces which together would produce the same effect as this one. It is evident that *OR* may be considered the diagonal of a parallelogram and an indefinite number of parallelograms may be constructed upon it, the two sides meeting at *O* being the components.

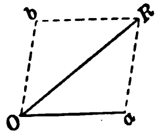
FIG. 23.



Resolution of forces.

Whenever one of the components is chosen as *Oa* in Fig. 24, then, it, with *OR*, fixes the parallelogram, so that the other component must be *Ob*. Thus *OR* is resolved into two forces which may be substituted for it. Frequent use is made of this principle in the study of mechanics.

FIG. 24.



Resolution of forces.

42. Moment of Force.

By *moment of force* is meant the *importance of the force*. It is much easier to turn a wheel by applying a force at the rim than at any point near the center. A force applied at the end of a long pump-handle is more effective than when the same force is used at the end of a short handle. It is easier to open or close a door by grasping the knob than by pushing or pulling at a point near the hinges.

Whenever the application of forces tends to produce rotation about an axis, that force will be most important which is applied farthest from the axis.

The moment of force, then, includes two elements, (1) the force itself, and (2) the distance of its point of application from the axis about which it tends to produce rotation.

The moment of force can always be found by multiplying the force by the perpendicular distance from the axis to the line of direction in which the force is exerted.

Thus, in Fig. 25A, the moment to the left of the axis is 6 *ob*, and to the right, 3 *oa*. If *ob* is 2 cm. and *oa* 4 cm., the number expressing the moments on each side of the axis is 12. In this case moments would be balanced and there would be no rotation about the axis.

Fig. 25A.

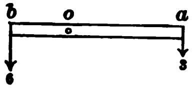
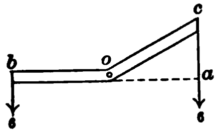


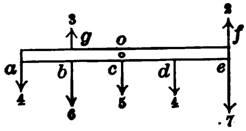
Fig. 25B.



In Fig. 25B, the rod is bent. The moment on the left is 6*ob*, but on the right it is not 6*oc*, but 6*oa*, *oa* being a perpendicular from *o* to the line of direction of the force. Since the forces are equal, then if *ob* and *oa* are equal, there will be equilibrium.

In Fig. 26 is shown a rigid rod 4 cm. long, with its axis of rotation at *o*. Suppose that a number of forces, *a*, *b*, *c*, *d*, *e*, *f*, *g*, are applied to it at different points. The magnitude of the forces in grams is indicated by the figures at the arrow-heads. The distance between the downward forces is 1 cm. *g* is one cm. to left of *o*, and *f* is 2 cm. to right of it. It is desired to find whether or not these forces are balanced, and if not, what force and where applied will produce equilibrium.

Fig. 26.



Equilibrium.

It is plain that the forces *a*, *b* and *f* tend to rotate the rod about *o* in a direction counter clockwise, while *d*, *e*, and *g* would produce a rotation clockwise. The force *c*, being directly beneath *o*, would have no effect in producing rotation either way.

Call all moments tending to produce the clockwise direction positive (+), and all tending to produce rotation in the opposite direction negative (—). Then, multiplying each force by its distance from the axis we have moments corresponding to the forces as follows:

$$\begin{array}{lrcrcr}
 & a, & 4 \times 2 & = & -8 \\
 & b, & 6 \times 1 & = & -6 \\
 & f, & 2 \times 2 & = & -4 \\
\hline
\text{Sum of moments} & & & = & -18
\end{array}$$

$$\begin{array}{lrcrcr}
 & d, & 4 \times 1 & = & +4 \\
 & e, & 7 \times 2 & = & +14 \\
 & g, & 3 \times 1 & = & +3 \\
\hline
\text{Sum of moments} & & & = & +21
\end{array}$$

The difference between these moments is thus found to be + 3. Consequently there will not be equilibrium but a rotation in a clockwise direction.

It is plain, then, that a force of 3 g. applied 1 cm. to the right of *o* and directed upward, or 1 cm. to the left of *o* and directed downward, will produce equilibrium. 1 g. at a distance of 3 cm. to the right of *o* and directed upward, or 3 cm. to the left of *o* and directed downward, would produce the same result.

The method just described will secure equilibrium as far as rotation about the axis is concerned. If it is also desired to remove all strain from the support *o*, we proceed as follows:

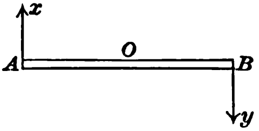
The sum of all the forces directed downward is 26 g. The sum of all forces directed upward is 5 g. The difference is 21 g. A force of 21 g. must then be applied at some point of the bar and directed upward that the sum of the forces in the two directions may be balanced. To prevent rotation the 21 g. must be applied at such a distance to the right of *o* that the product of 21 by this distance will equal 3. Hence the point is $\frac{1}{7}$ cm. to the right of *o*.

The axis *o* may be chosen at any point in the bar, or even beyond it at either end, and the same result of complete equilibrium will be obtained.

43. The Mechanical Couple.

When two parallel forces which are equal in magnitude and not in the same straight line act upon a body, they produce rotation but no motion of translation. Such an arrangement is called a *mechanical couple.* Since the two forces, x and y, Fig. 27, are equal, parallel, and opposite, the resultant force is zero, consequently no single force can be applied so as to produce equilibrium.

FIG. 27.



Mechanical couple.

If the axis of rotation is O, then the moment of force on one side is $x \times AO$, and on the other, $y \times BO$. The sum of these moments is $x \times AB$, since $x = y$ and $AO + BO = AB$. Hence the moment of force of a mechanical couple can be found by multiplying either force by the distance between the forces.

Problems.

1. How many dynes would equal a force of one pound? *Ans.* 444,518.

2. A mass of 20 g. is free to move and is acted on by a force of 500 dynes. How much faster will it be made to move each second? *Ans.* 25 cm.

3. What force will be required to give to a mass of 25 pounds an acceleration of 10 feet per second. *Ans.* 250 poundals.

4. How many dynes in 25 g.? *Ans.* 24,500.

5. How many pounds of force would equal 483 poundals? *Ans.* 15.

6. What is the magnitude and direction of the resultant and equilibrant of two parallel forces acting toward the north? One force is 30 dynes and the other 50 dynes. Construct vectors lines on proper scale to represent the conditions and results.

7. Two forces, 6 and 8 poundals, act at an angle of 90°. What will be the resultant? *Ans.* 10 poundals.

8. Two vector lines, one 6 cm. and the other 10 cm. long, diverge at an angle of 30°. Each centimeter is taken to represent 10 dynes. Construct a parallelogram of forces and determine the magnitude of the resultant by the graphical method. *Ans.* 154 dynes.

9. Find, by the graphical method, the resultant of eight forces; 6 pounds toward the north, 8 pounds toward the northeast, 12 pounds toward the east, 5 pounds southeast, 20 pounds south, 10 pounds southwest, 7 pounds west, and 15 pounds northwest.

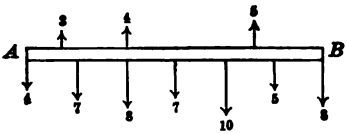
10. A given vector line represents a force of 50 dynes. Construct two other lines representing forces which would together produce the same effect. An indefinite number of sets of components may be drawn. Construct and measure three sets.

11. If, in Fig. 25A, *oa* were twice as long as there given, what force would need to be substituted in place of 3 to produce equilibrium.

Ans. 1½.

12. *AB* in Fig. 28 is a rigid bar 60 cm. long. On one side are seven parallel forces each having a magnitude in dynes as marked. These forces are spaced equally along the bar. On the other side are three forces acting in an opposite direction. The force of 3 dynes is 5 cm. from the end *A*; the one of 4 dynes, 20 cm. from *A*; and the one of 5 dynes is 15 cm. from *B*; find the magnitude and direction of the resultant. Find the magnitude and direction of the equilibrant and the point at which it must be applied to produce equilibrium.

FIG. 28.



Parallel forces.

Ans. The resultant is 37 dynes in the same direction as that of the seven forces.

The equilibrant is 37 dynes in a direction opposite to that of the resultant, and applied at a point $33\frac{29}{37}$ cm. from *A*.

CHAPTER IV.

MECHANICS.

MOTION.

44. Position.

The position of a point can be located only by reference to some other point. A point is located when its distance and direction from a known point are given. If the position of *A* is known, and *B* is 25 km. northeast of *A*, *B* can be found. The position of any object, however, is only relative to some other object. There is no point in the universe which is fixed and absolute, to which all other objects may be referred. Any convenient body may be chosen for reference, as a city, a lake, an island, or a star.

45. Motion.

Motion is a continuous change of position. Any change in either the distance or direction by which a point is located constitutes a motion. If the change of position is one of distance only, the motion is in a straight line. If the change is only one of direction, the motion is in a circle. A body may be at rest, but only in the sense that it does not change its position in relation to another body. Both bodies may at the same time be in motion in relation to a third body. The cars of a train are at rest in relation to each other, though all may be in rapid motion in relation to objects by the way. Motion also is only relative. When two trains are running side by side in the same direction and with the same speed, neither train has any motion in relation to the other, but both may be in rapid motion in relation to the ground. Suppose the first is moving northward at the rate of 30 miles an hour, and the second, 50 miles an hour in the same direction, as judged by an observer on the ground. If, then, the motion of the two trains be considered in relation to each other only, an observer on the fast train could consider the motion of the other as 20 miles an hour in a southern direction. If the observer is on the slow train he could consider the other as having a speed of 20 miles in a northern direction.

The earth is moving in its orbit at a rate of about 18½ miles per second. When it dashes into a cluster of shooting stars, it appears that the stars only are moving, while, in fact, the greater part of the motion is that of the earth.

Thus all motion is purely relative and there is no point in the universe which can be said to be at rest and to which all motions might be referred.

46. Velocity.

Velocity is the rate at which the position of a point or body is changed. It is the time-rate of change of position. It involves both the rate of change and the direction of the motion. It can therefore be represented by a line whose length would be proportional to the velocity and whose direction would be the direction of the motion.

The term *speed* is often used to indicate simply the rate of change of position, as when we speak of the speed of a race horse as one mile in two minutes, without any thought of the direction of the motion.

47. Uniform Velocity.

When the change of position is the same during each successive unit of time, the motion is *uniform*, that is, the distance passed over in each successive second, or other unit of time, is the same. When we say that the velocity of a moving body is 980 cm. per second, we do not mean that the motion is uniform at that rate, but that at the moment of observation the velocity is such that if the body would continue a uniform motion at that rate, the distance passed over in the next second would be 980 cm.

A railroad train may run at the rate of 75 miles an hour over a short stretch of good road. We mean by this that if this rate could be maintained for one hour, the distance passed over by the train would be 75 miles.

Uniform velocity for any considerable length of time is seldom found in nature or machines.

48. Average Velocity.

When the space passed over is not the same during successive seconds, sometimes greater, sometimes less, or, at times, no motion at all, the motion is said to be *variable*. An example would be the trip of a train from, say, New York to Chicago. The train runs very rapidly at some points, more slowly at others, and stops at intermediate stations.

In such cases it is easy to calculate the *average velocity*, that is, the velocity which the moving body would have had if its motion had been uniform between the two points considered. The distance from New York to Chicago is about 900 miles. If the time required to make the trip is 20 hours, then the average velocity is 45 miles an hour. It does not matter what speed or what stops the train may have made at various points of the trip, it is only necessary to know the distance between the two cities, and the time required for the train to move from one to the other.

Let s represent the whole space passed over, and t, the time, then

$$\text{average velocity} = \frac{s}{t}$$

49. Accelerated Motion.

An *accelerated motion* is one that changes its velocity in each successive unit of time. When the acceleration is such as to increase the velocity it is sometimes called positive acceleration or simply accelerated motion. When it is such as to decrease the velocity, it is called negative acceleration or retardation.

The *acceleration* itself is the *amount of increase* or *decrease* in the velocity in a unit of time.

When the amount of increase or decrease in velocity is the same for each successive unit of time, the motion is said to be *uniformly* accelerated.

When the change of velocity is not the same for each successive unit of time, the acceleration is said to be variable.

When a body of matter *free* to move, (that is, meets no resistance) is acted on by a force which is *constant*, (that is, has the same intensity all the time) the motion which results will be *uniformly accelerated.*

When the force is not constant, the motion will have a variable acceleration.

50. Uniformly Accelerated Motion.

A constant force, as already explained, will give to a free body the same increase in velocity during each second that it acts.

It must be understood that a *constant force* is one that keeps up with the moving body and exerts the same force upon it whether the body is just beginning its motion or has acquired a great speed.

During any second, then, the constant force will increase the velocity just as much as during the first second. If this increase, or acceleration, be multiplied by the number of seconds during which the force acts, the product will be the velocity at the end of that time.

Let v represent velocity; a, acceleration; and t, time. Then

$$(1)\quad v = at$$

The total *space* passed over by a body moving with uniform acceleration is found by multiplying the average velocity by the time. The average velocity is the rate at which the body must move uniformly to traverse the space in the given time.

Since the increase of motion is uniform, the average may easily be found by adding the velocities at the beginning and end of the time and dividing the sum by 2.

The velocity at first is 0, and at the end of t seconds, as shown above, it is at. Hence the average is $\frac{0 + at.}{2}$

The average velocity per second, multiplied by the number of seconds, will give the whole space passed over.

$$\frac{0 + at}{2} = \tfrac{1}{2}at$$

$$\tfrac{1}{2}at \times t = \tfrac{1}{2}at^2$$

Let s represent the space or distance, then

$$(2) \quad s = \tfrac{1}{2}at^2$$

If t is 1 sec., s will equal $\frac{1}{2}a$. That is, when the motion is uniformly accelerated, the distance passed over during the first second is equal to one-half the acceleration per second. If the distance traversed in the first second is known, the acceleration can readily be found by multiplying by 2.

The formulæ (1) and (2) are the two fundamental formulæ in all accelerated motion.

The laws expressed in these two formulæ may be stated thus:

In uniformly accelerated motion:

(1) *The velocity is equal to the acceleration multiplied by the time.*

(2) *The space passed over is equal to one-half the acceleration multiplied by the square of the time.*

By a proper combination of these two formulæ, other useful formulæ may be derived. Thus, from (1)

$$v = at$$

$$\therefore \; t = \frac{v}{a}$$

$$\therefore \; t^2 = \frac{v^2}{a^2}$$

Substituting this value of t^2 in (2)

$$s = \tfrac{1}{2}a \frac{v^2}{a^2} = \frac{v^2}{2a}$$

$$s = \frac{v^2}{2a}$$

$$\therefore \quad (3)\ v^2 = 2as, \text{ or } v = \sqrt{2as}$$

Formula (3) gives the relation between *velocity* and *space*, so that if either one is known the other may be determined without knowing the time.

It is obvious that the distance passed over by a body in *any one second*, is the difference between the total distances passed over at the end and at the beginning of that second.

By equation (2) the whole distance is $\frac{1}{2}at^2$.

When the time is one second less, the distance is $\frac{1}{2}a(t-1)^2$. Hence, letting d stand for the distance traversed by the body in any second,

$$d = \tfrac{1}{2}at^2 - \tfrac{1}{2}a\,(t-1)^2$$

$$d = \tfrac{1}{2}at^2 - \tfrac{1}{2}at^2 + \tfrac{1}{2}a\ 2t - \tfrac{1}{2}a$$

$$(4)\ d = \tfrac{1}{2}a\,(2t-1)$$

Suppose it is desired to know how far a body will move *during* the 11th second when the acceleration per second is 100 cm. By the formula,

$$d = 50 \times 21 = 1050 \text{ cm.}$$

When a body already has a velocity, and a constant force is made to act upon it in the same direction, the accelerations per second will simply be added to the initial velocity and (1) will become

$$(5)\ v = V + at$$

where V represents the initial velocity.

Likewise (2) becomes

$$(6)\ s = Vt + \tfrac{1}{2}gt^2$$

Vt is the distance the initial motion would have carried the body even if the constant force had not acted at all. This distance, then, must be added to that caused by the constant force.

Formula (3) evidently changes to

$$(7)\ v = V + \sqrt{2as}$$

and (4) changes to

$$(8)\ d = V + \tfrac{1}{2}a\,(2t - 1)$$

When the constant force is applied to a moving body in a direction opposite to its motion, the formulæ (4), (5), and (6) will be applicable in this case also, except that the effect of the constant force must be subtracted from the initial velocity, since the force tends to stop the motion.

In this case we have

$$(9)\ v = V - at$$

$$(10)\ s = Vt - \tfrac{1}{2}at^2$$

$$(11)\ v = V - \sqrt{2as}$$

51. Examples illustrating the Use of the Formulae.

The velocity, space, time, acceleration, and initial velocity are quantities involved in the formulæ given above. When the proper data are given, any one of these may be calculated. Thus,

Given *time* (t) 10 sec., and *acceleration* (a) 4 cm. per sec., to find *velocity* (v). It is seen that formula (1) contains the two given quantities and the unknown quantity required. Hence

$$v = 4 \times 10 = 40 \text{ cm. per sec.}$$

Given *time* 5 sec., and *acceleration* 20 cm. per sec., to find the *space* passed over.

Formula (2) contains the three quantities under consideration. Hence

$$s = \tfrac{1}{2} \times 20 \times 5^2 = 250 \text{ cm.}$$

Given *space* 500 cm., *time* 10 sec., to find *acceleration.*

Formula (2) is again the proper one for the reason given above. Hence

$$500 = \tfrac{1}{2}a \times 10^2$$
$$500 = 50a$$
$$a = 10 \text{ cm. per sec.}$$

Given *space* 40 feet, *acceleration* 20 feet per sec., to find *velocity*.

Formula (3) is the only one that contains these three quantities and none others. Hence

$$v = \sqrt{2 \times 20 \times 40}$$
$$v = 40 \text{ feet per sec.}$$

A body is moving with a *uniform velocity*, *V*, of 20 cm. per sec. A constant force in the same direction adds *10 cm. per sec.*, *a*, to the initial velocity. To find the *velocity* at the end of *5 sec.*

This problem gives numerical values to all the letters of formula (5) except v, which is to be found. Hence

$$v = 20 + 10 \times 5$$
$$v = 70 \text{ cm. per sec.}$$

If, in the same problem, the force had acted in a direction opposite to that of the initial velocity, formula (9) would have given $v = 20 - 50 = -30$ cm. per sec. That is, the force would have, in that time, stopped the body and given it a velocity of 30 cm. per sec. in the opposite direction.

52. Newton's Laws of Motion.

Sir Isaac Newton in the latter part of the seventeenth century announced three fundamental laws which are universally true and are of great importance in science. They are as follows:

(1) *A body at rest remains at rest, and a body in motion continues its motion uniformly in a straight line, unless acted upon by an external force.*

(2) *A given force has the same effect in producing motion*

whether the body upon which it acts be in motion or at rest, and whether it acts alone or with other forces at the same time.

(3) *To every action there is an equal and opposite reaction.*

53. The First Law.

The first law given above is a concise statement of the principle of *inertia.* The subject has already been discussed under Properties of Matter. The first part of the law is a statement which is in accordance with common experience. Most bodies of matter with which we are familiar are at rest under the action of balanced forces. The "external force" mentioned in the law is a force which is not balanced by another force or by a resistance equal to the force. A stone on the ground may be considered at rest. The force of gravity which is constantly active upon it is balanced by the resistance of the ground. It is the unbalanced force which causes bodies at rest to move. or changes the motion of bodies already in motion.

That the body will continue its motion in a straight line does not so clearly conform to our common experience. We have never observed a body that moves with uniform motion in a straight line for any great length of time. It can, however, always be shown that when the motion of a body is changed either in speed or direction, some force has been active in producing the change. A projectile, fired from a cannon, would, if entirely free from any outside influence, continue its motion forever with a uniform velocity in the direction in which it started. This is in accordance with the general principle of inertia that a body of matter will persist in whatever state it may be.

54. The Second Law: Momentum.

Momentum is the amount of motion. It includes two factors, the *mass* and the *velocity* of the moving body. The momentum is equal to the product of the mass by the velocity. If M represents the momentum, then, by formula,

$$M = mv.$$

A given force acting for a certain time will impart a certain velocity to any free body of matter. If the same force be applied to a greater mass, the velocity will be proportionately less but the momentum will be the same in all cases where equal forces act for equal times. The product of the force by the time during which it acts is often called the *impulse*. If F represents the force, and t the time, then

$$\text{Impulse} = Ft.$$

Since $v = at$, as already shown, the velocity varies as the time, and consequently for the same force and the same mass,

$$Ft. = mv.$$

The momentum produced is thus proportional to the impulse. If t is increased, v will increase in the same proportion.

If m becomes less, it is obvious that v must become greater, for mv must equal Ft.

For illustration, when a ball is shot from a rifle the explosive force of the powder is exerted equally to drive the ball in one direction and the gun in the other. The time of the application of the force is equal in both cases, hence the momentum of the gun is equal to that of the ball. But the mass of the gun is so great compared to that of the ball, that the velocity of the gun may be very small and yet the product, mv, in the two cases be equal.

Suppose the mass of the ball is ½ oz. and the velocity with which it leaves the gun, 1500 feet per second. Then its momentum expressed in these units is 750. Suppose the gun weighs 150 oz., then its velocity need be only 5 feet per second that its momentum may be equal to that of the ball. Since the impulses which produced the momentum in each case are equal, the same impulse applied in an opposite direction will bring either the ball or the gun equally to a state of rest.

Any given impulse has the same effect in producing or changing momentum whatever motion the body may have at the time when the impulse is applied.

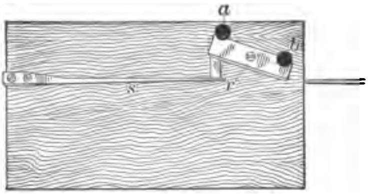
When a ball is shot horizontally, it begins to fall the moment it leaves the muzzle of the gun, and will reach the ground in the same time as one dropped from the gun to the ground. The impulse from the powder and from gravity each have their full effect, and consequently the time allowed for the horizontal flight can only be as long as that required for the direct fall to the ground.

The Second Law should then be stated with the understanding that *force* means *impulse* and *motion* means *momentum*.

Experiment 10.

There are several devices by which it can be shown that a body projected horizontally will fall to the floor in the same time as one let fall from the same height.

FIG. 29.



Horizontal projection.

A simple contrivance for this purpose is shown in Fig. 29. The stick *r* may rotate about the screw through its center. *a* and *b* are marbles or metal balls. *a* rests upon the board in front of *r*, while *b* rests upon a thin sheet of metal fastened to the under side of *r*. A hole of considerable size extends through the board directly beneath *b*. A strong spring, *s*, when pulled back and released, will propel *a* horizontally and, at the same time, remove the support from beneath *b*, just as the paper was removed from beneath the coin in Experiment 3, and the ball will then drop through the hole.

Hold the board firmly upon a table in a horizontal position. The sounds produced by the balls striking the floor should be heard at the same time.

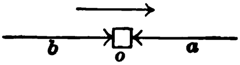
By "action" is meant the application of force. As has already been explained, no force, however small, can be exerted unless there is a resistance—"reaction"—exactly equal to that force.

If two men are pulling in opposite directions at the end of a rope, either one may be considered as producing the *action* and the other, the *reaction*. Neither man can increase the force of his pull unless the reaction is equally increased. This may be illustrated by use of two spring scales, one fastened to each end of a cord. Whatever the tension of the cord, the reading of the scales will be equal.

The action and reaction are thus the two mutual forces of a *stress*, as already explained.

When two forces, *a* and *b*, Fig. 30, act directly opposite to each other upon a body, *o*, no motion will result as long as *a* and *b* are equal. But, let *a* represent 60 dynes and *b*, 100 dynes. Then there is an excess of 40 dynes in the direction of the arrow above *o*. This force will result in the motion of the body, *o*. If the mass of *o* is 10 g., then the acceleration produced by the 40 dynes will be 4 cm. per second, for $F = ma$. This force must be added to *a* as it is in opposition to *b*. Thus the force in each direction is 100 dynes, and again the action and reaction are equal.

Fig. 30.

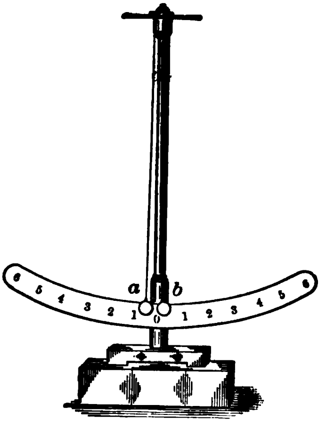


Action and reaction.

When one moving body strikes another, the action is called an *impact*. In this case the action and reaction are measured by the momentum of the moving body or bodies.

Case 1. Let two elastic balls, *a* and *b*, Fig 31, be suspended so that they just touch each other. Let the mass of one be equal to the mass of the other. If *a* be drawn aside and allowed to swing, as a pendulum, against *b*, the impact will cause both balls to be compressed for a moment. Since they are elastic, *b* will,

Fig. 31.



Impact.

in regaining its shape, react on *a* and bring it to rest, while *a* will act on *b* and give it the same momentum that *a* had at the time of impact. Since the balls have equal masses, *b* will move on just as *a* would have done if *b* had not been in the way.

Thus the action and reaction, as measured in the momentum of the two balls, are equal.

Case 2. Suppose the mass of *a* is twice as great as that of *b*, and that the operation is repeated as described above. In this case, *b* will receive the same momentum as before, but *a* will not be brought to rest because its momentum at the time of impact is twice as great as in the first case. So *a* will continue its motion after impact, but with only half the velocity that it had before impact.

Here, again, the action and reaction are equal.

Case 3. Suppose the balls covered with a thick layer of putty or clay. They may then be considered inelastic. If their masses are equal and *a* is allowed, as before, to swing against *b*, they will adhere to each other and move on with half the velocity of *a* just before impact.

The result here is plainly similar to that in Case 2.

Innumerable changes may be made in the kinds and conditions of impact, and it will be found in all cases that, while the total momentum is unchanged, the division of the momentum between the bodies concerned in the impact will be in accordance with the Third Law of Motion.

56. Velocity Vectors.

Since velocity has both magnitude and direction, it is a vector quantity.

The relation and combination of the vectors are much the same as those of force.

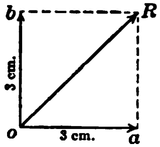
Let lines be drawn of such a length that each centimeter will represent a velocity of 20 cm. per second. Let the directions on this page be considered the same as on a map.

Then *oa*, Fig. 32, will represent a velocity of 60 cm.

per second toward the east, and *ob*, the same velocity toward the north.

If both these velocities are impressed upon a body, *o*, at the same time, the resultant velocity can be found by constructing a parallelogram and drawing a diagonal, just as was done in the case of forces. The resultant in this case is the vector *oR*, the magnitude of which is 84.85 cm. per second, and the direction toward the northeast.

FIG. 32.

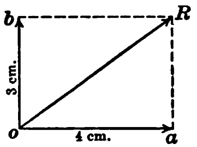


Vector lines of velocity.

When a number of velocities are combined, the resultant is found in the manner illustrated in Fig. 22.

The resolution and the composition of velocities are effected in the same manner as in the case of forces. Thus, suppose *oR* represents 50 miles an hour. This line may be resolved into two others, say, *oa* 40 miles an hour and *ob* 30 miles an hour at right angles to *oa*. This means that a body having a velocity *oR*, moves directly eastward with a velocity of 40 miles an hour, and directly northward, 30 miles an hour. These two velocities, at the same time, result in a velocity of 50 miles an hour in the direction *oR*, because 40 and 30 are the legs of a right-angled triangle of which the hypotenuse is 50.

FIG. 33.

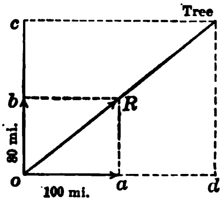


Resolution of velocity.

In illustration of the composition of velocities, suppose a train is running at the rate of 80 feet a second, and it is desired to hurl a projectile from the train with a velocity of 100 feet a second in a direction perpendicular to the motion of the train, in such a manner as to hit a tree 200 feet to one side of the track.

In this case we draw lines showing the magnitude and direction of the velocities of the train and projectile. Suppose each inch represents a velocity of 10 feet a second. Then draw *oa* 10 inches long to represent the velocity of the projectile, and *ob* 8 inches long and perpendicular to *oa*, to represent the velocity of the train. The projectile will retain the velocity of the train, *ob*, in addition to the velocity of projection, *oa*, and consequently will have the velocity *oR*.

FIG. 34.



Projectile thrown from moving train.

Since the tree is 200 feet away, two seconds must elapse before the projectile, at velocity *oa*, will have reached a point that distance from the track. During that time the projectile will have been carried forward by the train-velocity a distance of 160 feet. Hence the projectile must be thrown at such a point that the train will travel 160 feet before reaching a point opposite the tree.

57. Curvilinear Motion.

According to Newton's First Law, a body in motion will move in a straight line unless it is compelled by some outside force to change its direction. Accordingly, whenever a body is observed to be moving in a curved path, it can with certainty be concluded that some outside force is acting upon it.

58. Motion in a Circle.

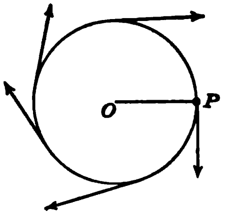
When a body is thrown in a horizontal direction, it does not move in a straight line but curves down to the earth. Its motion is the resultant of two forces, one of which acts in a horizontal direction and the other, gravity, in a vertical direction.

A curve is the result.

When a constant force acts upon a body in a direction at right angles to its motion, the result is motion in a circle. A weight attached to a cord and revolved about the hand is an example of this kind of a motion. The weight, *P*, Fig. 35, constantly tends to move in a straight line, tangent to the circle. The cord OP exerts a constant force which pulls P aside and into a circular path.

The force pulling P toward the center is called the *centripetal force*, and the inertia of the body, which resists the centripetal force, is often called the *centrifugal force*.

FIG. 35.



Curvilinear motion.

In fact, however, there is no force exerted outward from the center and tending to repel P from O. There is only the tendency of the body, P, to continue in a straight path, while the centripetal force is constantly exerted toward the center of the circle.

If the cord should break, the body would continue its motion in a direction at right angles to the cord at that instant.

59. Examples of Curvilinear Motion.

There are numerous examples of curvilinear motion resulting from the action of centripetal force. The earth and the planets move in nearly a circular orbit as a result of the attraction of the sun at the center of the circle. The attraction of the earth forces the moon into its orbital path.

A heavy fly-wheel may be rapidly rotated if the material is strong enough to resist the tendency of the heavy rim to move on in a straight line.

An emery wheel is firmly cemented together so that it may be rapidly rotated without flying to pieces.

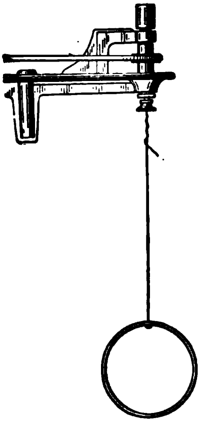
A carriage or train in rapid motion can turn a sharp curve only when there is a centripetal force sufficiently great to prevent a continuation of motion in the former direction.

A "centrifugal wringer" consists of a cylindrical cage which may be rapidly rotated. When wet clothes are within it, the adhesion of the water to the clothes is not sufficiently strong to resist the tendency to continue in a straight line, and the water is thrown from the cage. When the rotation is sufficiently rapid, the clothes are thus made almost dry.

Experiment 11.

Suspend a metal ring, about 15 cm. in diameter, by a cord about 30 cm. long, from a rotating apparatus. As the rotator is turned the ring will change its position so that its plane will be horizontal. In this position it will be rotating around its shortest axis.

FIG 36.



Rotation on the shortest axis.

In place of the ring, try a loop of a chain or a piece of a board. In all cases the rotation will be around the shortest axis.

The reason for this is that more of the matter of the rotating body can thus rotate in a circle of greater radius, and consequently can come more nearly to a motion in a straight line.

60. The Formula for Centripetal Force.

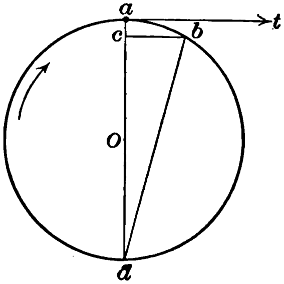
A formula by which the centripetal force can be calculated may be derived as follows:

Suppose a body *a* to be revolving in the direction of the arrow (Fig. 37) about the center *O*. Since the centripetal force is perpendicular to the direction of the motion it can have no effect in accelerating or retarding the motion in the circle. Hence the motion is uniform.

Let *ab* represent the space traversed by the body in a very small interval of time. Then the arc *ab* and its cord will not differ sensibly in length and one may be used in place of the other.

If the body had been left to itself, it would have moved in the direction *at*. Consequently, in passing from *a* to *b* it has been drawn from a straight course by a distance *ac*.

FIG. 37.



Curvilinear motion.

Since the triangle *abd* is inscribed in a semicircle, it is right angled at *b*, and since *bc* is perpendicular to the hypotenuse, the triangles *cab* and *bad* are similar. Hence

$$ac : ab = ab : ad$$

While the body moved from *a* to *b*, it was pulled from its course a distance *ac*. Hence *ac* is the distance the body is moved in the first unit of time by the constant force directed toward the center. Hence *ac* equals one-half the acceleration.

$$ac = \tfrac{1}{2}a \ (\S\ 50)$$

Since *ab* is the distance traversed in the unit of time, it is the velocity of the moving body. Hence

$$ab = v$$

The diameter of the circle is *ad*. Hence

$$ad = 2r$$

Substituting these values in the proportion,

$$\tfrac{1}{2}a : v = v : 2r$$

$$\therefore a = \frac{v^2}{r}$$

It has already been shown (§ 32 and § 50) that the force is measured by the product of the mass times the acceleration produced. That is,

$$F = ma$$

Substituting the value of *a* above,

$$F = \frac{mv^2}{r}$$

Thus, *the centripetal force varies directly as the mass and the square of the velocity, and inversely as the radius.*

For example, suppose a mass of 40 g. is attached to the end of a string 60 cm. long, and rotated about the hand with a velocity of 100 cm. per second.

$$F = \frac{40 \times 100^2}{60} = 6666.66 \text{ dynes}$$

The dynes are absolute units of force and may readily be reduced to gravitational units, if so desired, by dividing by 980 (§ 34).

$$\frac{6666.66}{980} = 6.8 \text{ g.}$$

A force of 6.8 g. must be exerted by the hand to keep the mass in the circle under these conditions.

If the data had been given in pounds and feet, the formula would have given the result in poundals, which could then have been reduced to pounds by dividing by 32.2 (§ 34).

Problems.

1. A train runs from station *A* to station *B*, a distance of 20 miles, in 30 minutes; from *B* to *C*, a distance of 60 miles, in 1½ hours; was delayed at *C* for one hour; run from *C* to *D*, 60 miles, in one hour. What is the average speed from *A* to *D*?

Ans. 35 miles per hour.

2. If a body at rest is acted on by a constant force which gives to it a uniform acceleration of 20 cm. per second, when will the velocity be 700 cm. per second? (§ 50). *Ans.* At end of 35th second.

3. How far will a body move in 25 seconds if its velocity is increased 10 m. each second? *Ans.* 3125 m.

4. A body is moving uniformly with a velocity of 80 cm. per second. A constant force applied in the same direction gives to it an acceleration of 20 cm. per second. With what velocity will the body be moving after it has traversed 40 cm. beyond the point where the force is applied? *Ans.* 120 cm. per sec.

5. What velocity will a constant force of 40 dynes give to a mass of 8 g. in 3 sec.? (§ 54). *Ans.* 15 cm. per sec.

6. Two inelastic bodies, moving in opposite directions, collide. One has a mass of 60 g. and moves with a velocity of 30 cm. per sec. The other has a mass of 30 g. and moves 20 cm. per sec. What will be the momentum and velocity of the combined mass after impact. (§ 55).

Ans. Momentum, 1200 C. G. S. units. Velocity, 13⅓ cm. per sec.

7. A boat is rowed at the rate of 100 feet a minute directly across a stream in which the velocity of the current is 5 miles an hour. The time of crossing the stream was 10 minutes. What was the velocity of the boat and where did it land? (§ 56).

Ans. Vel., 451.22 feet per min. Landing, 4400 feet below the point toward which the boat was at first directed.

8. The rim of an iron fly-wheel weighs 2500 pounds. It is made to rotate at the rate of 600 revolutions a minute. The diameter of the wheel is 6 feet. What centripetal force will be needed to hold the rim to a circular motion? (§ 60.) *Ans.* 919,571.7 pounds.

9. A body has three velocities forced upon it at the same instant. The velocities are 30, 40, and 80 cm. per second, and the angles between any two adjacent directions are all equal. Find, by the graphical method (§ 40) the magnitude and direction of the resultant velocity.

10. Make a list of the formulæ used in this chapter. Give the interpretation and derivation of each.

NOTE.—The formulæ may all be placed upon the blackboard and if a student can, before the class, readily give the explanation of the meaning, application, and derivation of each, he is learning physics. It may take some time, but it will be time well spent.

CHAPTER V.

MECHANICS.

GRAVITATION.

61. Law of Gravitation.

The law of universal gravitation may be stated as follows:

Every body of matter in the universe attracts every other body with a force which is directly proportional to the product of the masses considered, and inversely proportional to the square of the distance between their centers.

Expressed in formula,

$$F \propto \frac{mm'}{d^2}$$

where F stands for the force of gravitation, m and m' for the masses, and d for the distance between their centers.

This great law was discovered by Sir Isaac Newton and announced in the latter part of the 17th century.

No law is more firmly established nor has a wider application in the natural world.

62. Explanation of the Law.

According to this law, any two bodies, such as books, houses, or planets, are attracted toward each other. The force of the attraction is not readily detected when the masses of the bodies are small. By use of very delicate instruments, however, it is possible to detect and measure the force of gravitation between bodies of moderate size.

Two heavy metal balls may lie near each other and there appears to be no force tending to draw them together. But this is because the force is very small for such masses, and the resistance to their motion is much greater than the force can overcome. If the two balls could be so placed that they would be perfectly free to move, they would slowly come together.

If one ball were made twice as large, the force of attraction would be twice as great. If the mass of both balls were doubled, the attraction would be four times as great, that is, each body attracts the other in proportion to their masses, and hence as the product of the masses.

As the distance between the bodies is changed, the attraction is found to vary inversely, not as the distance, but as the square of the distance.

When the masses are very large, as that of the earth, the sun, or the planets, the attraction between them and other bodies is very apparent. A very great attractive force exists between the earth and the sun and they would at once begin to move toward each other were it not that the earth is revolving about the sun and all the attraction is needed as a centripetal force to keep the earth in its orbit and prevent its motion in a straight line tangent to the orbit.

A mass of 100 pounds is strongly attracted toward the earth, but not more strongly, in proportion to the masses, than it is attracted by another mass of 100 pounds when the distances are the same.

63. Constant of Gravitation.

The law of universal gravitation tells us how the force varies, but it gives no way by which to calculate how much the force is. We must know the force of attraction between certain given masses at a known distance apart, then this force can be used as a unit in measurement of the force between other masses at different distances, according to the general law.

It has been found by experiment that when two masses, one gram each, are placed so that the distance between their centers is one centimeter, the force of attraction between them is .000000066576 dynes. This is a very small fraction of a dyne, but it is the same for any kind of matter at any place, and so is called the *constant of gravitation.* It is usually designated by the letter G.

The general formula may now be written

$$F = G\frac{mm'}{d^2}.$$

If the masses are each 1 g. and the distance 1 cm., then

$$F = G\frac{1 \times 1}{1} = G.$$

But suppose the masses are 100 kg. and 1000 kg. and the distance is 100 cm. Then

$$F = .000000066576 \frac{100000 \times 1000000}{100^2} = .66576 \text{ dynes.}$$

In this way it would be possible to calculate the force of attraction between the earth and a stone upon its surface, if their masses and the distance between their centers were known.

64. Gravity.

Gravity is the name applied to the attraction of the earth for bodies on or near its surface. This is only a name applied to universal gravitation as it is observed on the earth.

Numerous experiments and every-day experience shows that the force of gravity varies with the mass. Two bushels of wheat weigh twice as much as one bushel because the mass is twice as great and consequently the force of gravity is doubled.

The mass of the earth remains the same at all times and any change in the force of gravity is attributed to a change in the quantity of matter which we weigh or handle.

For bodies above the surface of the earth, the force of gravity varies inversely as the square of the distance from the center of the earth.

The radius of the earth is about 4000 miles, so that small differences in distance would make very little difference in the force. At a point 4000 miles above the surface, the force, according to the law, would be one-fourth as great as at the surface.

For bodies beneath the surface, the force of gravity varies directly as the distance from the center. This statement is not rigidly true because the interior of the earth is more dense than the surface.

65. Mass.

The mass of a body is the amount of matter which it contains. The mass is a constant quantity and remains unchanged whether the body is on the earth, or out in space alone, or is transported to the moon or the sun.

The mass may be measured in absolute units by the acceleration which a given constant force will produce in it in a unit of time.

It has been shown (§ 32) that

$$F = ma.$$

If we know the *force* and the *acceleration* produced, it is then easy to calculate the *mass*.

Let a certain mass of lead be placed in a light cart which is supposed to run on a smooth track without friction. If the cart now be pulled along by a dynamometer (spring scales) and the force be kept constant at, say, 1000 dynes, and the increase of speed each second is found to be 25 cm. then,

$$1000 = m\,25$$
$$\therefore m = 40\,g.$$

The gram, here, is not weight but a unit of mass called the gram.

It is plain that this method of finding the mass of a body would be very inconvenient in the ordinary business transactions of the world. It is never used except in special scientific investigations.

66. Weight.

The weight of a body is the force of gravity exerted upon it. It is seen, then, that *mass* and *weight* are very different things. Mass is the *amount of matter*, while weight is the *force of gravity* upon that matter.

Since the force of gravity is, at any point, a constant force which varies with the mass, it can be very conveniently used to measure the mass. If the force of gravity is 20 dynes on one body and 40 dynes on another, we conclude at once that the mass of the latter body is twice as great as that of the former, for reasons given in the next paragraph.

67. Force of Gravity varies as the Mass.

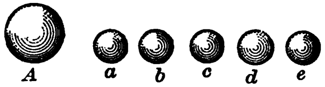
It can easily be shown that if two pieces of iron, or other material, one large and the other small, be dropped together from some high elevation, as from an upper window of a building, they will fall together and reach the ground at the same instant.

The force of gravity, therefore, must have given to each mass the same acceleration.

So, since $F = ma$ in each case, and a in one case is equal to that in the other, then the two forces must have been exactly proportional to the two masses.

This is illustrated in Fig. 38. A is a sphere having the same mass as a, b, c, d, and e together. It is evident that the sum of the forces on the small spheres would not change if they were all melted together into one which would then have the same mass as A. The force on a is one-fifth of that on A, but the mass of a is also one-fifth, and so they will have the same acceleration and will fall together.

FIG. 38.



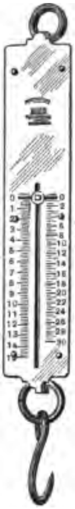
Gravity proportional to mass.

68. Weighing.

For reasons given above, it is plain that masses of bodies may be compared with each other or with standard masses by the method called *weighing*. One method of determining the mass of a body is by use of *spring scales*. This instrument is based upon a principle known as Hooke's law, stated as follows:

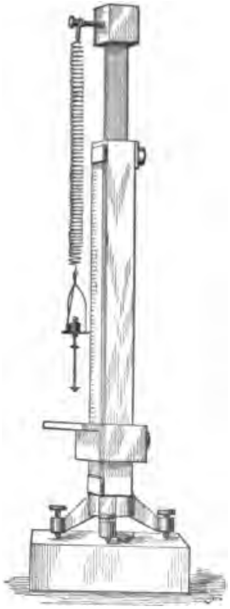
The strain of an elastic body is proportional to the stress (§ 31).

FIG 39.



Spring scales.

FIG. 40.



Jolly balance.

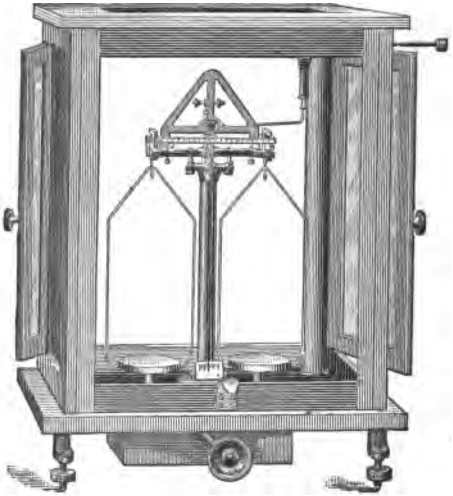
According to this law, a coiled spring will be stretched a distance which is proportional to the force pulling on one end of it.

Such spring coils are very extensively used to determine mass and force of gravity.

In Fig. 39 is shown the ordinary spring scales, or balances, which have been constructed and graduated according to the principles just given.

In Fig. 40 is shown a more delicate instrument but one constructed on the same principles. It is known as Jolly's balance because a man by that name first introduced it. Its value lies in the fact that, since the wire is not very stiff and the coils are long, even small changes in the force will cause very marked changes in the length of the coil. In this way very slight differences in mass can be detected.

FIG. 41.



Beam balance.

For very delicate weighing, a beam balance, such as shown in Fig. 41, is necessary. This consists of a beam with pans hanging from each end and mounted at its center on a hard, sharp edge. A long pointer is fastened to the middle of the beam and reaches to a scale at the bottom of the post so that the least movement of the beam can be detected by observing the position of the pointer on the scale.

If there is any excess of mass in one of the pans, it will cause an unbalanced moment of force (§ 42) resulting in a rotation of the beam on its axis.

Numerous kinds of balances are constructed, but the underlying principle of all of them is that the force of gravity, which they measure, is exactly proportional to the mass which we wish to determine.

69. Variation of Weight.

Since weight is not inherent in a body but is dependent on an outside force—gravity, then the weight will change whenever the force changes.

We have already shown that, for objects above the surface of the earth, the force varies inversely as the square of the distance from the earth's center. Hence the weight of a body grows less as it is raised above sea level.

If a weight of 1000 pounds is raised to the top of a mountain 5 miles high, the distance from the center of the earth is increased from 4000 to 4005 miles, and the weight at that point may be found by the proportion,

$$x : 1000 = 4000^2 : 4005^2$$
$$\therefore x = 997.5 \text{ pounds.}$$

It is thus shown that the same mass weighs 2.5 pounds less at that height,

If the weight of 1000 pounds could be lowered beneath the surface of the earth to a point, say, 3000 miles from the center, then, according to the second law of § 64,

$$3000 : 4000 = x : 1000$$
$$\therefore x = 750 \text{ pounds.}$$

This latter law is true only on the assumption that the earth has the same density all the way through. In fact, however, the density of the earth increases from the surface toward the center. The weight of a body will increase to a certain depth below the surface and from there on to the center the weight will decrease.

The nature of the interior of the earth is not well known and no definite law can be given on this point.

There is a difference of about 26 miles between the polar and equatorial diameters of the earth. Consequently, an object at the north or south pole would be about 13½ miles nearer the center of the earth than it would be at the equator. As a result of this, a body at the equator will weigh about $\frac{1}{568}$ less than at the poles. A mass which weighs 568 pounds at one of the poles, would weigh 567 pounds at the equator.

The rotation of the earth on its axis also causes objects to weigh less at the equator than at the poles. The earth, in round numbers, is 25,000 miles in circumference. An object at the equator will complete this circle once every 24 hours. Its linear velocity would thus be more than 1000 miles an hour. Objects on either side of the equator would move in circles which are smaller, the nearer they are to the poles. Consequently, bodies at the equator would require a greater centripetal force to prevent motion in a straight line (§ 57) than at any other point on the earth's surface. For this reason, the apparent force of gravity at the equator is $\frac{1}{289}$ less than at the poles.

$$\frac{1}{289}+\frac{1}{568}=\frac{1}{192}\text{ (nearly)}.$$

For the two causes given, a body will weigh $\frac{1}{192}$ less at the equator than at the poles.

70. Changes in the Force of Gravity as shown by Balances.

The changes in the weight of objects under the different conditions just described are made apparent by use of a spring balance, but not by the beam balance.

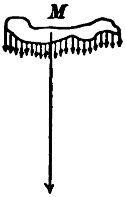
In the former the spring is stretched in accordance with Hooke's law (§ 68) and when the force of gravity changes, the index attached to the spring will change its position accordingly.

In case of the beam balance, however, known weights are balanced against a certain mass, and any change in the force of gravity will affect the masses in the two pans alike. Consequently they will still balance.

71. Center of Gravity.

The center of gravity of a body is a point about which a body is balanced, in whatever position the body is turned. In other words, it is a point such that if a line drawn through it in any direction is considered an axis of rotation, the moments of force due to gravity on one side of the line are exactly balanced by the moments on the other side.

Fig. 42.

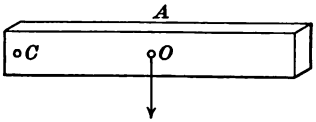


Center of gravity.

In Fig. 42 let M be an irregular mass of any kind of matter. Suppose the body be considered as made up of a large number of small masses, say one gram each. Then the force of gravity on each will be one gram or 980 dynes, (§ 33). If each of these forces be represented by lines, the lines will be parallel and directed downward. The resultant of all these forces is their sum, and its point of application is such that the moments of force on all sides of it are balanced (§ 36), no matter in what position the body may be placed.

The whole weight of a body may be *supposed* to be at the center of gravity. This will often greatly assist in certain calculations in mechanics. For example, A, in Fig. 43, is a bar of metal weighing 500 g. It is desired to know the moment of force tending to produce rotation about the pivot C. The center of gravity of the bar is found to be at O, 10 cm. from C. The whole weight of the bar is now supposed to be at O, for there is the point of application of the resultant, and the moment of force is then $500 \times 10 = 5000$ C. G. S. units,

Fig. 43.



Center of gravity.

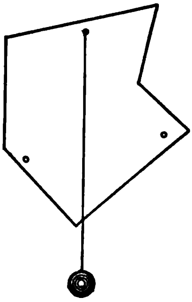
In homogeneous masses having regular shapes the center of gravity is at the center of the body.

The center of gravity and center of mass are at the same point.

Experiment 12.

Suspend a piece of board in such a manner that it will swing freely from its support.

FIG. 44.



Center of gravity.

From what has been said, we know that the center of gravity of the board will be in a line directly downward from the support. To find this line, suspend a weight by a cord from the same support. With a pencil, make a line on the board directly beneath the cord. The center of gravity will be somewhere in this line.

Now suspend the board by another point and draw a line in a similar manner. The center of gravity will also be in this line, and consequently must be at the intersection of the two lines. It is not on the surface, but half-way through the board at this point.

72. Equilibrium.

It has been shown (§ 42) that there is complete equilibrium when all forces and moments are balanced. That is, a body in complete equilibrium will have no motion of any kind.

That is one kind of equilibrium. We will now discuss equilibrium of a somewhat different character, namely, the state of a body in reference to the force of gravity.

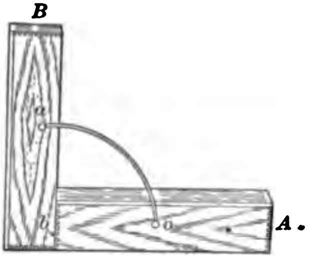
Three kinds of equilibrium of this character are usually described,—*stable, unstable, and neutral.*

73. Stable Equilibrium.

A body is said to be in stable equilibrium when, if slightly disturbed, it will fall back to its original position. It may oscillate back and forth, but will finally settle back to the position it had before it was disturbed. A pendulum with a heavy bob is a good example of a body in stable equilibrium.

A heavy box laid on its side is another example of this kind of equilibrium, for if it is raised a short distance on one edge and then let go, it will fall back to its first position.

FIG. 45.



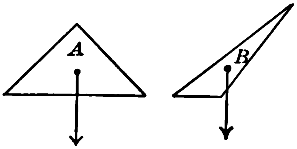
Equilibrium.

The reason for this stability lies in the fact that when the body is disturbed in the manner described, the center of gravity, and hence the whole weight, (§ 71) will be raised, and if it is not supported, it will, of course, fall back.

This is illustrated in Fig. 45. The box on its side may be considered as having all its weight at *o*, the center of gravity. If the end *A* be raised, the point *o* will be moved along the curve *oa*. When the box has reached the position *B*, the whole weight has been lifted a distance *ba*.

When the box is standing on one end, it is again in stable equilibrium, but not so stable as before, for now it may be pushed over without raising its center of gravity so great a distance as before.

FIG. 46.



Equilibrium.

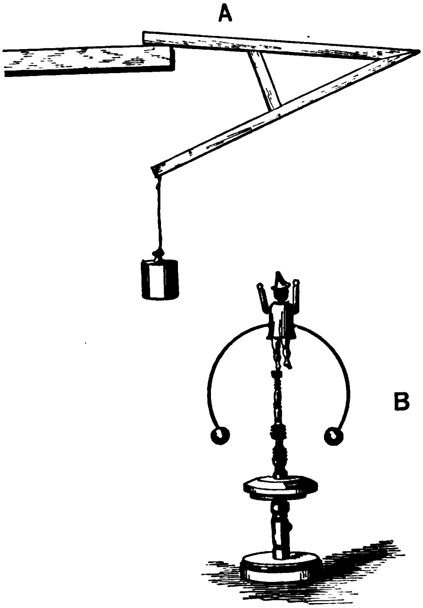
A line let fall vertically from the center of gravity is often called *the line of direction.*

A body will not fall over as long as the line of direction falls within the base upon which the body is supported. In the triangle, *A*, Fig. 46, the line of direction falls within the base of support, and so it will stand, but *B* will fall, because its center of gravity is not supported.

A large base of support gives stability to a body, because then its weight must be raised a considerable distance before it will topple over.

Stability is also increased by making the center of gravity as near to the base as possible. Lead or other heavy material is often used in the bases of stands, ink wells, and so on, to lower their center of gravity. This increases the stability because a greater weight must now be raised before the body can be pushed over. A wagon loaded with hay may fall over much more easily than when loaded with the same weight of stone or iron, because the center of gravity of hay and wagon is higher.

FIG. 47.



Stable equilibrium.

When a body is suspended, and the center of gravity is below the point of suspension, the equilibrium will be stable. Examples of this are a pendulum, a swing, a picture hanging on a cord, and so on.

Experiment 13.

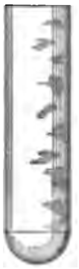
The device shown at *A*, Fig. 47, is a light wooden frame with a heavy weight attached. When suspended as shown, the center of gravity will be below the point of support and in the line of direction. The condition is therefore one of stable equilibrium, although the figure has the appearance of instability. For the same reason, the figure of the boy, *B*, is also in stable equilibrium.

Experiment 14.

Fasten a hemisphere of some heavy material, such as lead, to a cylinder of pith about one inch long, as shown in Fig. 48. Because the pith is so light, the center of gravity of the two will still be in the body of the lead though moved slightly toward the pith. This device is sometimes called a "witch," because when it seems to be standing, it is in fact lying down, and vice versa. However the "witch" may be disturbed, it will always regain the position shown in the figure.

The phenomenon can easily be explained by imagining a line of direction drawn through the center of gravity and remembering that a body will be at rest only when the line passes through the point where the body is supported.

FIG. 48.

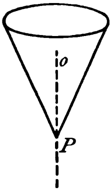


"Witch."

74. Unstable Equilibrium.

A body is in unstable equilibrium when the base of support through which the line of direction passes is only a point. The cone resting on its apex is unstable. The center of gravity is at *o*, Fig. 49, and the line of direction, *oP*, passes through the point upon which the cone is supported. The cone will be at rest in this position as long as the conditions just named continue; but a very slight disturbance will cause the line of direction to fall to one side or the other of *P*. A movement of the cone does not, in this case, involve a rise in the center of gravity. Consequently there will be no force tending to bring the cone back to its first position.

FIG. 49.



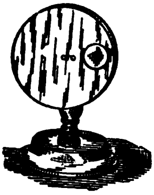
Unstable equilibrium.

There are all grades of stability, from the most stable to the unstable, the latter being the condition of least stability.

75. Neutral Equilibrium.

A body is said to be in a state of neutral equilibrium when it can be moved without either raising or lowering its center of gravity. A cone on its side, or a sphere, are examples, if the mass of which they are composed is evenly distributed. The cylinder shown in Fig. 50 would be in neutral equilibrium if it were homogeneous, but the lead plug inserted at one side of the center moves the center of gravity from the center of the cylinder toward the lead. Consequently the equilibrium is stable, if the cylinder be placed upon the table with the lead plug below the center. If the cylinder be supported at the center of mass, as shown in the illustration, the equilibrium is neutral.

FIG. 50.



Equilibrium.

76. Falling Bodies.

A falling body is one which moves toward the center of the earth under the action of the force of gravity.

The force of gravity may be considered constant for all points in a body's descent at any place near the earth's surface.

A constant force produces uniformly accelerated motion (§ 50).

A falling body, then, as long as it meets no resistance, is governed by the same laws as any freely moving body under the action of a constant force.

Hence the laws of motion discussed in § 49 are applicable to the motion of falling bodies.

77. Effect of Mass on Acceleration.

It has already been shown (§ 67) that when the mass of a body is increased, the force of gravity increases in the same proportion. Consequently, a heavy body will fall with the same velocity as a light one.

When the acceleration is once determined for any point on the earth's surface, it will be the same for all bodies at that place.

78. Effect of Air on Falling Bodies.

When we speak of *freely* falling bodies we mean that the bodies will meet no resistance during their fall. The air, however, offers considerable resistance to bodies moving rapidly through it. For dense substance, such as iron, lead, and other metals, the resistance is not large; but feathers, snow flakes, and other light bodies, are very perceptibly checked in their fall because they present such a large surface to the air in proportion to their weight.

This may be shown by use of a long glass tube containing a feather and a bullet. When the air is nearly all pumped from the tube the feather will fall as rapidly as the bullet from end to end as the tube is turned.

79. Formulæ for Falling Bodies.

The formulæ for falling bodies are exactly the same as those for any motion which is uniformly accelerated. The formulæ which were worked out in § 50 may then be used here except that in case of falling bodies it is customary to use *g* instead of *a* for the acceleration, since *g* is the first letter of *gravity*.

The formulæ may then be given as follows:

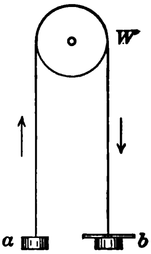
1. $v = gt.$
2. $s = \frac{1}{2}gt^2.$
3. $v^2 = 2gs.$
4. $d = \frac{1}{2}g(2t-1).$
5. $v = V + gt.$
6. $s = Vt + \frac{1}{2}gt^2.$
7. $v = V + \sqrt{2gs}.$
8. $d = V + \frac{1}{2}g(2t-1).$
9. $v = V - gt.$
10. $s = Vt - \frac{1}{2}gt^2.$
11. $v = V - \sqrt{2gs}.$

The value of *g* varies with the locality on the earth's surface (see Table III, Appendix), but for all places in or near the latitude of 40° its value will be sufficiently correct if taken at 980 cm., or 32.2 feet, per second. This value may be used for *g* in any of the formulæ.

80. Experimental Proof of the Formulæ.

When a body falls it soon acquires such a rapid velocity that it is very difficult to mark the exact space it passes over during each second. It is possible, however, by means of a device like that shown in Fig. 51, to determine the character of the motion due to gravity and have the motion so slow that distances passed over during each second can be accurately measured. *W* is a light wheel which rotates almost without friction. Over the wheel passes a light silk cord to the ends of which are attached weights of, say, 10 g. each. The weights will balance each other and there will be no movement.

FIG. 51.



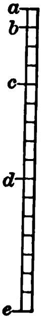
Falling body.

Now place upon *b* a rider weighing 1 g., and *b* will slowly fall while *a* will rise. A force of 1 g. is here moving a mass of 21 g. That is, the force is $\frac{1}{21}$ as great as that exerted by gravity, hence the acceleration produced is only $\frac{1}{21}$ as great.

If the distances passed over by *b* in its descent during each second be carefully marked and measured, it will be found that during the first second the distance was, say, *ab*, Fig. 52, but during the next second the distance is 3*ab*, in the third second 5*ab*, in the fourth second 7*ab*, and so on.

At the end of the first second the body must have had a velocity of 2*ab* because the force is constant and can only cause the body to move a distance *ab* in any second. So, since it passed over 3*ab* it must have had a velocity at the end of the first second which would carry it a distance 2*ab* in the second second. The velocity 2*ab* added to the 1*ab* due to gravity gives 3*ab* for the distance during the second second.

FIG. 52.



Acceleration of a falling body.

At the end of the second second it is seen that the velocity must have been $4ab$, which with the $1ab$ due to gravity, gives $5ab$ for the distance during the third second.

At the end of the third second the velocity would be $6ab$, which with the $1ab$ gives $7ab$ for the distance during the fourth second.

Thus it is seen that the velocities are $2ab$, $4ab$, $6ab$, and so on. That is, there is an increase in the velocity—an acceleration—of $2ab$ each second. But the distance during the first second is $1ab$, equal to *one-half* the acceleration. It is always true in case of uniformly accelerated motion that *the distance traversed in the first second is equal to one-half of the acceleration.*

We may call the distance moved during the first second $\frac{1}{2}g$, and tabulate the results of the experiment as follows:

1	2	3	4	5
Number of seconds.	Distance traversed during each second.	Velocity at end of each second.	Increase of velocity or acceleration.	Total distance passed over.
1	1 $\frac{1}{2}g$	2 $\frac{1}{2}g$	2 $\frac{1}{2}g$	1 $\frac{1}{2}g$
2	3 $\frac{1}{2}g$	4 $\frac{1}{2}g$	2 $\frac{1}{2}g$	4 $\frac{1}{2}g$
3	5 $\frac{1}{2}g$	6 $\frac{1}{2}g$	2 $\frac{1}{2}g$	9 $\frac{1}{2}g$
4	7 $\frac{1}{2}g$	8 $\frac{1}{2}g$	2 $\frac{1}{2}g$	16 $\frac{1}{2}g$
5	9 $\frac{1}{2}g$	10 $\frac{1}{2}g$	2 $\frac{1}{2}g$	25 $\frac{1}{2}g$
6	11 $\frac{1}{2}g$	12 $\frac{1}{2}g$	2 $\frac{1}{2}g$	36 $\frac{1}{2}g$

Now turn to § 79 and notice that the *first* formula is easily derived by comparing columns 1 and 3 above. The *second* formula can be directly deduced from columns 1 and 5. The *fourth* formula is easily obtained by comparing columns 1 and 2.

All the other formulæ are readily derived from these three.

The kind of motion observed in this experiment, is exactly the same as that of a freely falling body, and when the value of g is once determined for any locality, the other quantities may at once be determined. When metric units are used, g may be taken as 980. In English units, 32.2.

81. Effect of throwing a Body Upward or Downward.

Gravity, like any other force, produces the same effect whether the body upon which it acts be in motion or at rest (§ 52). When a body is thrown vertically downward it will move with uniform motion at the velocity with which it is thrown, and in addition will be affected by gravity just as if it had started from rest. All such problems, then, can be solved by use of formulæ 5, 6, 7, and 8 (§ 79).

When a body is thrown vertically upward, the conditions are the same except that gravity now will cause motion directly opposite to that of the initial motion. In cases of this kind, use formulæ 9, 10, and 11 (§ 79).

The uniform and the accelerated motions are to be considered separately and then added or subtracted as the conditions may require.

Problems.

1. What is the gravitational force between two masses of 2000 kg. and 40,000 kg. when the distance between their centers is 2 m.? *Ans.* 133.152 dynes.

2. What is the mass of a body when a force of 150 poundals will give to it an acceleration of 4 feet per second? *Ans.* 37.5 pounds.

3. If a mass weighing 1000 g. at the surface of the earth were raised 1000 miles above the surface, what would then be its weight? *Ans.* 640 g.

4. A cargo of 3840 tons of coal is loaded at a point on the equator and conveyed to the north pole. How much more will it weigh there? *Ans.* 20 tons.

5. A uniform beam 20 feet long weighs 100 kg. A weight of 50 kg. is suspended from one end of it. Where is the center of gravity of the whole of it? *Ans.* 6.66 feet from weighted end.

6. If a body falls from a position of rest for 6 seconds, what velocity will it acquire? *Ans.* 5880 cm. per. sec.

7. Through what distance will a body fall in 3 sec? *Ans.* 4410 cm.

8. If a body falls from rest through a space of 100 feet what will then be its velocity? *Ans.* 80.25 feet per sec.

9. Through what distance will a body fall during the 10th sec.? *Ans.* 305.9 feet.

10. A body is thrown vertically downward with a velocity of 200 cm. per sec. What will be its velocity in 5 sec.? *Ans.* 5100 cm. per sec.

11. A body is thrown vertically upward with a velocity of 1000 cm. per sec. where will it be at the end of 2 sec.? *Ans.* 40 cm. above the point whence it was thrown.

12. A bullet is shot vertically upward with a velocity of 2000 feet a sec. How long before the bullet returns? Neglect resistance of air. *Ans.* 2 min., 4.22 sec.

13. A body at Spitzbergen falls 491.54 cm. from a position of rest during the first second. What is the acceleration due to gravity at that place? *Ans.* 983.08.

14. A bullet is shot horizontally from the top of a building 144.9 feet high, with a velocity of 1500 feet a second. How far from the building will the bullet be when it strikes the ground? *Ans.* 4500 feet.

CHAPTER VI.

MECHANICS.

PENDULUM.

82. Definition of a Pendulum.

Any body which swings freely from a point of suspension and whose center of gravity is below that point, is a pendulum. Under the conditions named, the body will, when disturbed, oscillate back and forth, and finally, because of friction and resistance of the air, will come to rest with its center of gravity directly beneath the point of suspension. This, then, is a condition of stable equilibrium (§ 73).

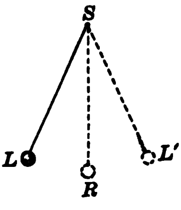
83. The Simple Pendulum.

A simple pendulum is one which has all its mass at one point, and this mass is connected to the point of suspension by a cord which is without weight. These conditions cannot be realized but we have a near approximation to it in the case of a lead ball suspended from a fine thread. By this arrangement the laws of the pendulum may be investigated.

84. Definitions and Terms.

Let SL, Fig. 53, represent a pendulum consisting of a lead ball suspended by a fine thread from the point S. The *length* of the pendulum is the distance from S to the center of the ball.

FIG. 53.



The distance from R to L or from R to L' is called the *amplitude* of vibration.

Vibration or *oscillation* are terms used to describe the swing of the pendulum.

A *single vibration* is a movement from one side to the other, as from L to L', and the time required is called the time of a single vibration.

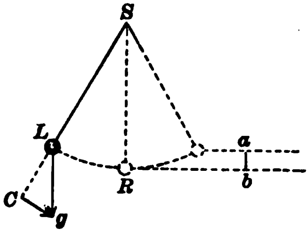
A *seconds pendulum* is one which makes a single vibration in one second. Its length changes with any change in *g*. Whenever the value of *g* is known, the length of the seconds pendulum can easily be calculated. It will not differ a great deal from 39.1 inches or 99.3 cm.

The *period* of vibration is the time required for two single vibrations, or, in other words, it is the time required for a pendulum to return in the same direction to the point at which the period began. Thus, the time required to move from *R* to *L*, then to *L'* and back to *R* is a period. The weight on the end of the pendulum is often called the *bob*.

85. The Force which causes the Pendulum to Vibrate.

Let a pendulum be set vibrating with an amplitude *RL*, Fig. 54. The bob will be raised vertically a distance *ba*, and the force of gravity will tend to bring it back again to the position at *R* where the line of direction will pass through *S* (§ 73).

FIG. 54.



Motion of a pendulum.

When the bob is at *R* the whole force of gravity acting upon it is in the direction of the thread *SR*.

But when the bob is at *L* a part of the force acts along the thread and another part at right angles to it.

Let *Lg* represent the force of gravity and resolve this force into its two components (§ 41) *LC* and *Cg*. *LC* is the part of the force which causes only a tension of the thread, while *Cg* is perpendicular to the thread and causes the motion of the bob.

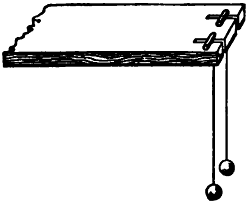
The component *Cg* disappears at *R* but the momentum of the moving bob carries it on to the other side, where a similar component of the force of gravity brings it back.

If the pendulum would meet no resistance it would never come to rest.

Experiment 15.

Prepare two pendulums by fastening lead balls to the end of silk threads about 120 cm. long. Fasten a piece of pine board rigidly to a firm support. Make two slits about 5 cm. apart in the end of the board. Slip the threads into the slits and raise or lower the lead balls until the distance from the under side of the board to the middle of the ball is 100 cm. Make sure that the two pendulums are alike in every respect. To test whether or not their lengths are equal, set them vibrating together and if, in the course of one or two minutes their periods continue to be equal, they may be considered of the same length.

FIG. 55.



Experimental pendulums.

1. Set one pendulum vibrating through a small arc, say, three degrees, and the other through an arc of six degrees. Let them swing for a minute and observe that the period of one remains the same as that of the other. The amplitude of the vibration does not change the period as long as the arcs are small.

2. Shorten the length of one of the pendulums until it makes two vibrations to the other's one. Measure carefully the length of the short pendulum and it will be found to be *one-fourth* as long as the other. That is, to make the period one-half as long it is necessary to make the length one-fourth as long. Further trial would show that to make the period one-third as long it would be necessary to make the pendulum one-ninth as long. To make the period twice as long it would be necessary to make the pendulum four times as long, and so on.

3. Replace one of the lead balls with another which is two or three times as heavy, being careful to have the centers of the two balls at the same distance from the support. Set both in vibration and observe that their periods remain unchanged. This might be expected from the principle explained in § 67.

4. Suspend an iron ball over a magnet and observe that the vibrations are more rapid and consequently the periods are shorter. From this we would infer that a pendulum will vibrate more rapidly at those points on the earth's surface where the force of gravity is greater.

86. Statement of the Laws of the Pendulum.

From very careful experiments the following laws are deduced.

(1) *The period of vibration is independent of the amplitude when the arc is small.*

(2) *The period of vibration varies directly as the square root of the length.*

(3) *The period of vibration is independent of the weight of the bob.*

(4) *The period of vibration varies inversely as the square root of g.*

87. The Pendulum Formula.

The laws of the pendulum may be expressed in the formula

$$P = 2\pi\sqrt{\frac{l}{g}}$$

where P is the period, l the length, g the acceleration due to gravity, and π (pi), 3.1416.

If the time of a single vibration is considered, the formula is

$$T = \pi\sqrt{\frac{l}{g}}.$$

By this formula it is possible to find the value of any one of the terms when the others are known.

88. The Use of the Formula.

Suppose it is desired to find the length of a seconds pendulum at a place where g is 980 cm. per second.

$$T = \pi\sqrt{\frac{l}{\ }}$$

$$\therefore\ 1 = \pi\sqrt{\frac{l}{980}}$$

Squaring both sides, $1 = \dfrac{\pi^2 l}{980}$

$$\therefore\ l = \frac{980}{\pi^2}$$

$$\because\ l = 99.3 \text{ cm.}$$

In a similar manner either g or T can be found when the other terms are known.

89. Finding the Value of g.

The pendulum is the best instrument known for determining the value of g at different places on the surface of the earth. The values given in the Appendix were found by this means.

An easy change in the arrangement of the formula above gives

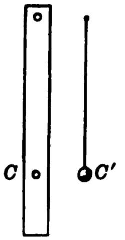
$$g = \frac{\pi^2 l}{t^2}$$

Hence, if the length of the pendulum and the time of a single vibration are accurately determined, the value of g can easily be calculated.

90. Compound Pendulum.

The compound pendulum,—also called the physical pendulum,—has its mass distributed at various distances from the point of suspension. A uniform rod or bar of any kind, suspended so that it will vibrate, is a compound pendulum. A heavy bob suspended by a wire is also compound because the wire has considerable weight. All actual pendulums are compound though some are a near approach to the simple pendulum.

FIG. 56.



Compound pendulum.

91. Center of Oscillation.

In every physical pendulum there is a point C, Fig. 56, at such a distance from the point of suspension that a simple pendulum of that length would vibrate in the same period. This point is called the center of oscillation.

Experiment 16.

Drill a small hole in a meter stick near one end. Suspend the stick from a small nail. From the same support suspend a lead ball by a fine thread. Vary the length of the thread until the ball and the stick vibrate in the same time. The center of the ball will then be directly over the center of oscillation of the stick. Drill a small hole in the stick at this point also.

Reverse the stick and suspend it from the center of oscillation. The period of vibration will be the same as before.

The experiment described above shows that the real length of a compound, or physical, pendulum is the distance from the point of suspension to the center of oscillation, and that these two points are reversible.

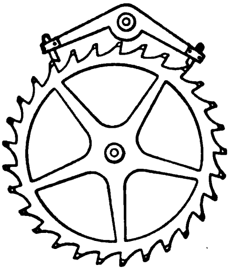
The center of oscillation is also the center of percussion, because the stick when held in the hand and struck upon a sharp edge at that point, will not jar or injure the hand.

92. Use of the Pendulum in Clocks.

The use of a pendulum as a means of keeping time was first suggested by Galileo. (See cyclopedia.) In the year 1583 A. D. he one day observed that the great chandelier which hung by a long chain from the ceiling in the tower of Pisa, swung back and forth in the same time whether the amplitude was large or small. The best method he then had of marking time was the beating of his pulse.

These observations suggested to him the idea of using the pendulum as an exact time-keeper, and he constructed a pendulum clock.

FIG. 57.



Escapement wheel.

A pendulum regulates the motion of a clock by allowing the escapement wheel to turn one notch in each vibration. An arm from the axis of the escapement lever gives a slight impulse to the pendulum in each vibration—just enough to overcome the resistance which would bring the pendulum to rest if it were left to itself.

The student should detach the hands and face from a pendulum clock and examine the operation while the clock is in motion.

Problems.

1. Make a drawing showing the resolution of forces at three different points along the arc through which the bob of a pendulum swings. (§ 85).

2. If a pendulum 400 cm. long makes a single vibration in 2 sec., how long will a seconds pendulum be at that place?

Ans. 100 cm.

3. How high is the ceiling of a room where a plumb bob suspended from the ceiling with the center of the spherical bob 10 cm. from the floor, makes a single vibration in 4 sec.? g. at the place is 980.

Ans. 15 m., 98.7 cm.

4. A pendulum which beats seconds at Cincinnati is carried to Spitzbergen. What will its time be there? (Appendix III.)

Ans. .998 sec.

5. If a seconds pendulum is 99.6 cm. long at a certain place, how many vibrations per minute will a pendulum 120 cm. long make at the same place? *Ans.* 54.67.

6. If the length of a seconds pendulum at a certain place is 99.5 cm., what is the value of g at that place? ($\pi^2 = 9.8696.$)

Ans. 982.0252

7. If one pendulum makes 60 vibrations while another makes 80, what is the ratio of their lengths? *Ans.* 1 : .5625.

8. If, in a certain locality, a body falls from rest and acquires a velocity of 2943 cm. in 3 sec., what is the length of the seconds pendulum there? *Ans.* 99.4 cm.

9. Why, in most clocks, is the bob of the pendulum made flat and caused to move edgewise through the air?

10. Explain the action of a clock when the bob of the pendulum is removed.

CHAPTER VII.

MECHANICS.

ENERGY AND WORK.

93. What Energy is.

Energy is the ability to do work, or, in other words, to move against resistance. A body may possess energy whether it does any work or not, but no work is ever done except by the expenditure of energy.

Energy is very abundant on the earth and very nearly all of it is derived directly or indirectly from the sun. Winds, running water, heat, coal, wood, oil, and food, all possess energy which came from the sun.

94. What Work is.

Work is the operation of overcoming resistance through space. Work is done in lifting a weight from the floor to the top of a table; in dragging a weight along the ground; in pulling a wagon up a hill. One does no work by simply pushing against a wall or holding a weight upon his shoulder. Work always involves the two elements of *force* and *distance*. This is usually expressed by the formula

$$W = Fs,$$

where W is work, F is force or resistance, and s is the space through which the force acts.

Since the amount of work done is always equal to the amount of energy expended, the units employed in measurement of one will serve as well for the other.

95. Units of Work or Energy.

The *foot-pound* is the work done by a force of 1 pound acting through a distance of 1 foot.

The *kilogram-meter* is the work done by a force of 1 kg. acting through a distance of 1 m.

The *foot-poundal* is the work done by 1 poundal acting through a distance of 1 foot.

The *erg* is the work done by 1 dyne acting through a distance of 1 cm.

These four important units should be clearly understood. The first two are based upon the gravitational units of force and the last two upon the absolute units (§ 33).

96. The Use of the Units.

If a workman carries a hod full of mortar weighing 80 pounds up a vertical 20-foot ladder, he will do 80 × 20 = 1600 foot-pounds of work. If the weight had been given in kilograms and the distance in meters the work would be expressed in kilogram-meters.

These units are used not only to measure work done against the force of gravity, but any kind of work where the forces, or resistances, are measured in gravitational units. Nearly all ordinary work is measured by these two units.

The foot-poundal and erg are much smaller units and are in common use in science.

If a mass of 10 pounds is given a velocity of 10 feet per second in 1 sec., the force must be 100 poundals. If this force is exerted through a distance of 5 feet, 500 foot-poundals of work is done. This can easily be reduced to foot-pounds by dividing by 32.2.

The erg, in a similar manner, may be reduced to gram-centimeters of work by dividing by 980, and this then can be reduced to kilogram-meters by dividing by 100,000 (Appendix IV).

97. Potential Energy.

Potential energy is the energy which a body possesses by virtue of its position or its affinity for other substances.

A mass on a table has potential energy in reference to the floor, for it may fall. When on the floor it would still have potential energy in reference to the ground or the bottom of a well. Whenever its position is such that it may fall it has available potential energy.

A coiled spring has potential energy because it will do work in uncoiling.

Water has available potential energy whenever it may fall to a lower level.

Coal, wood, and gas possess potential energy because they have a strong affinity for oxygen and, at the proper temperature, the carbon and oxygen will unite chemically. The energy consists in the fact that particles were once separated from other particles for which there was a strong affinity. The separation was effected by the sun at a time when the plants were growing.

98. Kinetic Energy.

Kinetic energy is the energy which a body has by virtue of its motion.

The motion of a mass of matter represents a certain amount of work which has been done upon the body. When the moving body meets resistance, it will give up part or all its energy, and thus does work upon other bodies.

A weight of 10 pounds may be lifted from the floor through a space of 3 feet to the top of a table. To do this, 30 foot-pounds of work must be done, and the body then contains 30 foot-pounds of potential energy.

If, now, the body be pushed off the table it will fall, and its potential energy will be completely converted into kinetic energy, the amount being exactly the same in either case.

When the mass and velocity of a moving body are known, its energy can easily be calculated by the formula

$$E = \tfrac{1}{2}mv^2.$$

This formula is derived from a consideration of the fact that

$$\begin{aligned} &(1) & F &= ma \text{ (§ 32)} \\ &(2) & v^2 &= 2as \text{ (§ 50)} \\ \text{and } &(3) & W \text{ or } E &= Fs \text{ (§ 94)} \end{aligned}$$

From (2), $a = \frac{v^2}{2s}$, and this value substituted in (1) gives $F = \frac{mv^2}{2s}$. This value of F substituted in (3) gives $E = \frac{1}{2}mv^2$.

Suppose a mass of 5 pounds is moving with a velocity of 40 feet per second, then

$$E = \tfrac{1}{2} \times 5 \times 40^2 = 4000 \text{ foot-poundals.}$$

This can be reduced to foot-pounds by dividing by 32.2.

Suppose a mass of 100 g. is moving with a velocity of 50 cm. per sec., then

$$E = \tfrac{1}{2} \times 100 \times 50^2 = 125{,}000 \text{ ergs.}$$

This can be reduced to gram-centimeters of energy by dividing by 980.

99. Power.

Power is the rate of doing work.

A small boy can do as much work as a man, but he cannot do as much in one hour or day. Whenever power is considered, the element of time enters into it. A power which can do 1000 ergs of work in a minute is one-half as great as one which can do 2000 ergs in the same time.

The unit of power usually employed is the *horse-power.*

One horse-power is equal to 33,000 foot-pounds of work in one minute, or 550 foot-pounds in one second.

If, for example, a weight of 1100 pounds is to be raised to a height of 300 feet in 1 minute, 330,000 foot-pounds of work must be done in that time. This work can be done by 10 horse-power.

100. Energy and Momentum compared.

It has already been shown (§ 54) that the momentum of a moving body is measured by the product of its mass and velocity, while we here see that energy is proportional to the *square* of the velocity.

The momentum of ten pounds moving ten feet per second is 100 as measured in feet and pounds, and the energy is

500 foot-poundals. If, now, the velocity is doubled, the momentum will also be doubled, but the energy will be *four* times as great.

The bullet which is shot from the gun has the same momentum as the gun itself, but much more energy.

This may be understood from the following: Suppose a loaded car is moving on a track. We may calculate both its momentum and its energy if we know its mass and velocity.

Its momentum is such that a certain force applied to the car in a direction opposite to its motion will in a certain time bring it to rest.

Now, suppose the car to have twice the velocity. The same force will have to be applied twice as long to bring it to rest.

But with twice the velocity and twice the time, the distance moved against the resistance will be four times as great. With three times the velocity the force would need three times the time, and so the distance would be nine times as great. That is, the distance a body moves against resistance varies as the square of the velocity. The product of the resistance by the distance through which it is exerted is a measure of the work done or the energy expended. Hence, $E \propto v^2$.

101. Conservation of Energy.

There is a certain amount of energy in the universe. This amount is never increased nor diminished. When energy disappears from one body it always appears in some other body. If a moving body is brought to rest by collision with another body, it loses its kinetic energy to the body with which it collided. The sun loses all the energy which the earth receives from it. The energy in steam is taken from the coal, and the energy in our own bodies is derived from the food we eat.

Thus, energy may be transferred from one body to another, or transformed in kind, but the sum of all the energy is a constant quantity.

This is the great principle of the *conservation of energy.* Energy does not exist except in association with matter, and so, matter may be defined as *the vehicle of energy.* Physics may be defined as *the science which treats of matter and the transferrence and transformation of energy.*

Problems.

1. A mass of ten pounds is moving with a velocity of 500 feet per sec. Find its kinetic energy. *Ans.* 38,819.9 foot-pounds.

2. A stone weighing 1 ton rests on a wall at a height of 50 feet above the pavement. What is its potential energy in reference to the pavement? *Ans.* 100,000 foot-pounds, or 50 foot-tons.

3. A mass of 10 pounds is raised from the ground to the height of 16.1 feet, and placed upon a shelf. Show that when the weight is allowed to fall it will, just as it strikes the ground, have the same amount of energy that it had when at rest on the shelf.

4. How much work in ergs must be done on a mass of 50 g. to give it a velocity of 20 cm. per sec ? *Ans.* 10,000 ergs.

5. How many kilogram-meters of work is done in raising 235 kg. to a height of 20 cm.? *Ans.* 47.

6. What must be the h.-p. of an engine to raise 20 tons of brick to the top of the third story of a building—45 feet—in one hour? *Ans.* $\frac{10}{11}$ horse-power.

7. What is the horse-power of an engine that can lift 60 cubic feet of water from a depth of 242 feet in one minute? Weight of a cubic foot of water, 62.5 pounds. *Ans.* 27.5.

8. How long will it take a 10 h.-p. engine to lift 40 tons of coal from a mine 300 feet deep? *Ans.* 1 hr., 12.7 min.

9. If a 5 h.-p. engine does 1,300,000 foot-pounds of effective work in 8 minutes, how much of its energy is ineffective? *Ans.* 20,000 foot-pounds.

10. How much work is done by a horse in pulling a load up a hill, the average force exerted being 250 kg. and the length of the hill being 300 m. *Ans.* 75,000 kgm., or 542,470 foot-pounds.

11. A car runs very smoothly upon a track so that its friction may be neglected. A man pushing with all his force for 1 minute is able to give to the car a velocity of 10 feet per sec. The car weighs 2,125 pounds. What fraction of a horse-power is the man-power? *Ans.* $\frac{1}{10}$, nearly.

12. A ball weighing 10 g. is shot vertically upward with a velocity of 5,000 cm. per sec. How much energy will it have when at the highest point of its flight? *Ans.* 125,000,000 ergs.

CHAPTER VIII.

MECHANICS.

MACHINES.

102. Definition of a Machine.

A machine is a contrivance by which energy may be transferred or transformed.

The steam engine and the dynamo are machines. The engine *transfers* energy to the dynamo and the dynamo transforms the energy into that of the electric current.

Machines do not of themselves do any work, but simply receive energy and then pass it on to other machines or bodies of matter.

Work in most cases can be done to a much greater advantage by the use of a machine, although a machine never passes on as much energy as it receives. Some energy is always used in overcoming the resistance due to friction.

103. Mechanical Advantage.

By use of a machine a small force may be greatly increased, as when a force is exerted on the long arm of a lever to raise a heavy weight on the short arm. The ratio of the two forces is called the mechanical advantage.

While the small force may raise a large weight, yet the distance through which the small force must move is proportionately greater than the distance through which the large force moves.

There is, then, an advantage of *force*, in this case, but a loss of *distance.*

By use of a machine a slow movement may be greatly increased, as when a force is applied to the short arm of a lever. In this case the mechanical advantage is a gain in velocity or distance with a proportionate loss of force.

These advantages are often very desirable, since they enable one to do work which would otherwise be impossible, but the amount of work in any case is the same whether the machine is used or not.

104. Kinds of Machines.

Machines are usually classified as *simple* and *compound*.

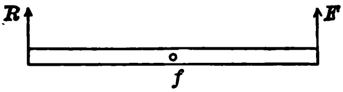
There are but two simple machines, namely, the *lever* and the *inclined plane*. Common forms of the lever are the bar, the pulley, and the wheel and axle. Common forms of the inclined plane are, any sloping plane, the wedge, and the screw.

A compound machine is simply a more or less complicated combination of the two simple machines. If the operating parts of any complex machine be carefully examined they will be found to be either levers or inclined planes.

105. The Lever.

The lever is a rigid bar with an axis about which it may rotate. The axis of the lever is called the *fulcrum*.

FIG. 58.

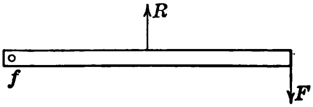


Lever of the first class.

There are three classes of levers, depending on the relation of the points of application of the force and resistance to the fulcrum.

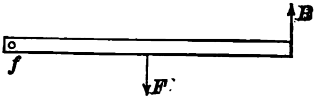
In Fig. 58, let *f* be the fulcrum, *F* the force, and *R* the resistance. In such an arrangement the lever is of the first class.

FIG. 59.



Lever of the second class.

FIG. 60.



Lever of the third class.

When the fulcrum is at one end and the resistance is between it and the force, as shown in Fig. 59, the lever is of the second class.

When the force is between the two other points, the lever is of the third class.

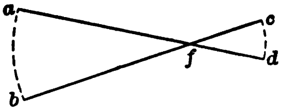
The distance from the fulcrum to the force is called the *force-arm*, and from the fulcrum to the resistance is called the *resistance-arm.*

106. Mechanical Advantage of Levers.

The advantage of a lever of the first class depends on the location of the fulcrum. If the fulcrum, *f*, Fig. 61, is half way between the force and resistance, there will be no advantage except that the resistance will be moved in a direction opposite to that of the force.

If the force-arm is longer, there will be an advantage in force exerted against resistance; but while force is moved through a distance, say *ab*, the resistance will be moved through *cd*.

FIG. 61.



Advantage of levers.

If the force-arm is shorter, the advantage will be in the distance or velocity moved by the resistance. If the force moves through *cd*, the resistance will be moved through *ba*.

In a lever of the second class the advantage is evidently always that of force, because the force-arm must always be longer than the resistance-arm.

In a lever of the third class the advantage is always that of distance or velocity, because the force-arm is always shorter than the resistance-arm.

107. Law of Machines.

The general law for machines is that *the product of the force by the distance through which the force moves is equal to the product of the resistance by the distance through which it moves.*

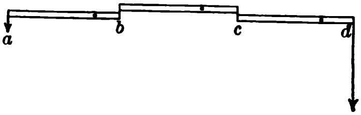
Since, in case of the lever, the distances moved are proportional to the arms, the special law for the lever is that *the product of the force by the force-arm is equal to the product of the resistance by the resistance-arm.* This is the condition of equilibrium discussed under the subject of moments of force (§ 42).

In case the lever is bent, the arms are the perpendicular distances from the fulcrum to the lines of direction of the force or the resistance, as explained in § 42.

108. The Compound Lever.

A system of levers arranged as in Fig. 62, is a compound lever. Suppose the force-arm of each lever is 12 cm. long and the resistance arm 3 cm. Then the mechanical advantage of each lever is 1 : 4. If the force downward at *a* is 10 g., the upward force at *b* will be 40 g. This will be increased to 160 g. at *c*, and 640 g. at *d*. Thus a force of 10 g. at *a* will balance a force of 640 g. at *d*. Any number of levers may be used.

FIG. 62.



Compound lever.

The mechanical advantage of such a system can always be found by multiplying together the ratios of the separate parts., Thus, in this case, the ratios are

$$\begin{array}{rcl} & & 1 : 4 \\ & & 1 : 4 \\ & & 1 : 4 \\ \hline \text{Product} & = & 1 : 64 \quad = \text{mechanical advantage of the system.} \end{array}$$

109. Pulleys.

A pulley is a grooved wheel mounted in a frame and capable of rotating freely upon its axis.

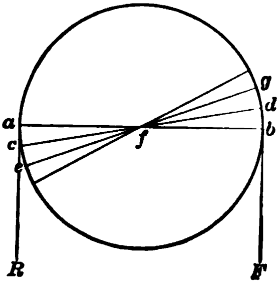
All pulleys are levers.

If, as shown in Fig. 63, a cord is placed over the pulley and a force is exerted downward at *F* against some resistance at *R*, the wheel becomes a lever with the fulcrum at *f*. The part of the wheel along the line *ab* is the only part in actual use while the pulley is in the position shown. When the force moves downward a short distance, the line *cd* will take the position *ab* and it will then be the lever. A little further, *eg* becomes the lever.

Thus the pulley may be considered as made up of an infinite number of levers which come into play one after another as the wheel is rotated.

A *fixed* pulley is one which is rigidly fastened to a support. A *movable* pulley is one which is supported by the cord or cable which passes through it. This pulley moves with the resistance.

FIG. 63.

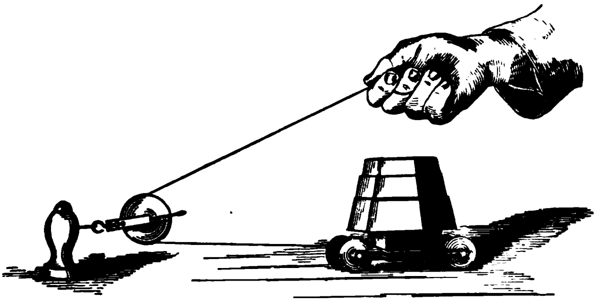


The pulley.

110. Mechanical Advantage of the Pulley.

In the case of the fixed pulley, Fig. 64, it is plain that the two arms of the lever are equal, and consequently, there is no advantage except that the resistance is moved in a direction opposite to that of the force.

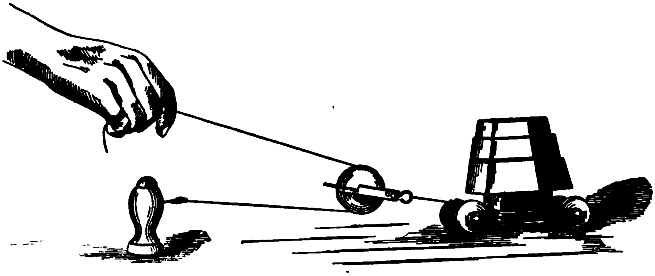
FIG. 64.



The fixed pulley.

The movable pulley is a lever of second class, as seen in Fig. 65, and the force-arm is always twice as long as the resistance-arm. The advantage in force then will always be as 1 : 2 in a single movable pulley.

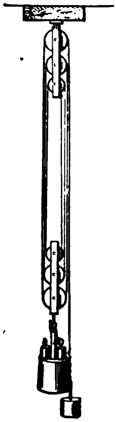
FIG. 65.



The movable pulley.

When several movable pulleys are fastened together and a continuous cord passed around them and the fixed pulleys, the mechanical advantage may be greatly multiplied. In the arrangement shown in Fig. 66, there are three movable pulleys. The resistance, a heavy weight, say, may be considered as equally distributed between the three. Each pulley, then, lifts one-third the weight, and so each strand of the cord must lift one-half of one-third, or one-sixth of the weight.

FIG. 66.

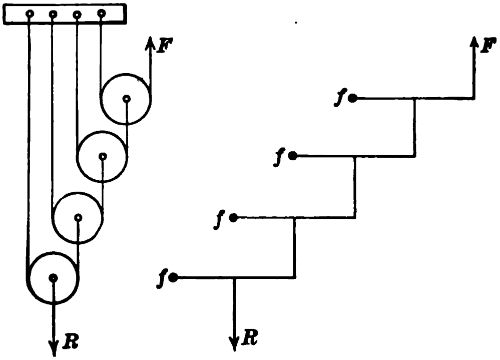


Pulleys combined.

The advantage may also be found by counting the number of strands of the cord upon which the weight is hanging. In this case there are six strands, each having a tension equal to one-sixth of the weight. The force at the free end of the rope need then be only one-sixth of the weight.

Pulleys are arranged in a variety of ways. The arrangement in Fig. 67 is interesting as an illustration of a compound lever of the second class. The ratio of gain of force is 1 : 2 for each lever, or pulley, and the advantage of the system of four is 1 : 16. This ratio may always be found for pulleys arranged in this manner by raising 2 to a power equal to the number of pulleys used.

FIG. 67.



Compound lever of the second class.

111. Work done by Means of the Pulley.

In considering the use of pulleys it must be clearly understood that while they are a great *convenience* in doing work, yet they do not *do* any of the work. They are simply a device through which work may be done advantageously. For example, a mason wishes to raise a stone weighing 800 pounds to the top of a wall 10 feet high. The work that must be done is 8000 foot-pounds. The mason cannot lift the stone directly, but he can attach it to a block containing, say, four movable pulleys. The weight will then hang upon eight strands of rope and he will have to pull only 100 pounds on the end of the rope. The stone will be slowly raised and when eighty feet of rope has been pulled down with a force of 100 pounds, the stone will have been raised to a height of 10 feet. There is evidently the same amount of work done, for

$$100 \times 80 = 800 \times 10,$$

but the mason is thus able to employ a small force through a long distance and accomplish work which otherwise would be impossible for him to do alone.

Experiment 17.

Arrange any system of movable pulleys and calculate the ratio of the weights which must be attached to the end of the cord and to the pulleys to produce equilibrium. The weight of the movable pulley must be added to the weight which is attached to it. Attach the weights, calling the small one the force, and the large one the resistance. Move the force through a fixed distance and measure the distance through which the weight is moved. Show that these distances are inversely as the weights.

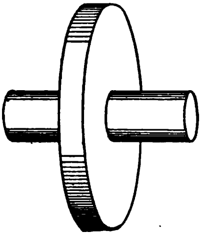
Reverse the names. Move the large weight up and down and notice the speed of the small weight and the distance it moves.

Establish the law that the product of the force by the distance through which it moves is equal to the product of the resistance by the distance it moves.

112. Wheel and Axle.

The wheel and axle is a form of lever of the first class. The long arm of the lever is the radius of the wheel, the short arm is the radius of the axle, and the fulcrum is the longitudinal axis of the axle. The mechanical advantage is the ratio between the radii of the wheel and the axle, or the ratio of the circumference of the wheel and that of the axle, since circumferences have the same ratio as their radii.

FIG. 68.



Wheel and axle.

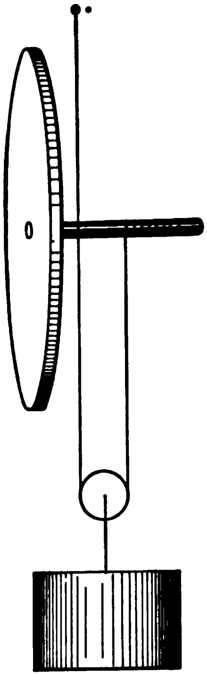
Suppose the circumference of the wheel is 900 cm. and that of the axle 30 cm. When the cord on the wheel is unwound through a distance of 900 cm., the wheel will have turned once around. At the same time the axle has turned once and has wound up 30 cm. of the cord attached to it. It is plain then, from the general law of machines (§ 107), that a force of 1 kg. on the wheel cord will balance 30 kg. on the axle cord.

113. A Compound Machine.

Suppose a compound machine is composed of a pulley and a wheel and axle as shown in Fig. 69.

To calculate the mechanical advantage of this combination the ratio for each machine may be found separately and the ratios can then be multiplied together as in the case of the compound lever (§ 108).

FIG. 69.



Compound machine.

Let the wheel and axle of Fig. 69 have the same dimensions as the one in the paragraph above. The ratio of gain for the single moveable pulley is always 1 : 2. Then

$$\begin{array}{rr} & 1 : 30 \\ \times & 1 : \ 2 \\ \hline = & 1 : 60 \end{array}$$

By use of this combination, then, the force is multiplied sixty times.

114. The Inclined Plane.

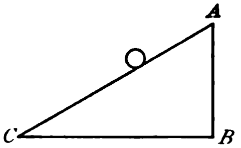
The inclined plane is frequently used in doing work where a large gain in force is desired. Let *AC*, Fig. 70, represent an inclined plane. Suppose a weight is to be raised from the level *CB* to the height *BA*. This may be done by lifting the weight vertically from *B* to *A* or by moving it along the incline from *C* to *A*. In either case the same amount of work is done, but in the latter instance a smaller force is used through a greater distance. Suppose the weight is 300 pounds, *AB*, 4 feet; and *AC* 10 feet. Since the amount of work is the same whether the weight is moved through *BA* or *CA*, then by the general law of machines (§ 107).

$$300 \times 4 = f \times 10.$$
$$\therefore f = 120.$$

Hence a force of 120 pounds exerted through the distance *CA* will accomplish the same end as 300 pounds through *BA*.

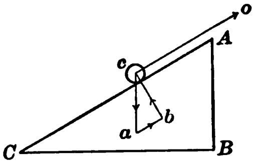
A better method of calculating the advantage of an inclined plane is by a resolution of the force. For example, let a cylinder weighing 300 pounds be held in place on the incline, Fig. 71, by a force directed along *co*, parallel to *CA*.

FIG. 70.



Inclined plane.

FIG. 71.



Force applied parallel to the incline.

The whole weight of the cylinder, 300 pounds, will be represented by the line *ca* which may be drawn of such length that each quarter inch represents 30 pounds. It will then be 2½ inches long.

The force represented by *ca* may be resolved into *cb* perpendicular to the incline, and *ab* parallel to it. The forces *bc* and *ab* exerted in the directions indicated by the arrowheads, will just balance the single force *ca*.

The value of *ab*, then, will be the force directed along *co*, and the value of *cb* will be the portion of the weight supported by the incline.

The triangles *ABC* and *abc* are similar right-angled triangles and hence have their homologous sides proportional.

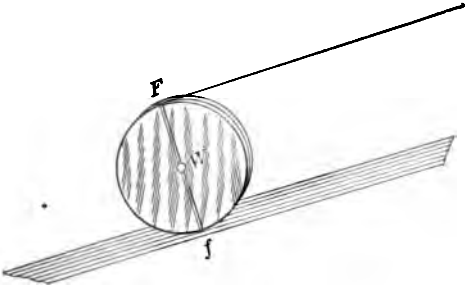
Suppose *AB* is 3 feet; *CB* 4 feet; and *CA*, consequently, 5 feet. Then, since the sides of the small triangle will have the same proportionate lengths and *ca* is already fixed at 2½ inches, *ab* must be 1½ inches long and *bc*, 2 inches.

But each quarter inch represents 30 pounds, hence the force parallel to *co* is 180 pounds, and the force perpendicular to the incline is 240 pounds. This is the graphical method.

Whenever a force is exerted parallel to an incline so as to produce equilibrium, the ratio of the force to the weight will be the same as the ratio of the height to the length of the incline. For example, a plank 12 feet long is raised 4 feet at one end. The ratio of height to length, then, is ⅓. If a barrel weighing 300 pounds is placed on the plank, a force equal to ⅓ of its weight, exerted parallel to the plank, will hold it in place. One man could, by this arrangement, lower such a barrel from the pavement into a cellar, by pulling with a force of about 100 pounds upon a rope attached to the axis of the barrel.

In case the rope is wrapped around the barrel, as shown in Fig. 72, the machine becomes compound, being composed of a lever of the second class and an inclined place. The whole weight of the barrel may be considered to be at the center, *W*, the force will be applied at *F*, and the fulcrum will be at *f*. Hence, other conditions being the same as above, a force of fifty pounds will support the barrel on the incline.

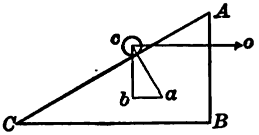
FIG. 72.



Barrel on incline.

In case the force is exerted parallel to the base of the incline, more force must be used because it is in part opposed by the incline itself.

FIG. 73.



Force exerted parallel to the base.

The resolution is similar to that above, and shows that the ratio desired in this case is that of the height to the base of the triangle, since cb, representing the whole weight, now corresponds to CB.

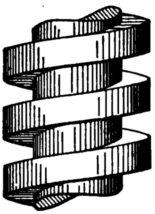
Using the same dimensions as in Fig. 71, we have $3 : 4 = ab : 300$ $\therefore ab = 225$ pounds. This is the force exerted along co. Also, $3 : 5 = 225 : ca$ $\therefore ca = 375$ pounds. This is the force on the incline.

It is not necessary to know the whole length and height of an inclined plane. The ratio of the height to the length is all that need be known for these calculations. For example, a hill rises one foot in ten, and it is desired to know what force a horse must exert on a load of one ton to draw it up the hill. We say at once that the force must be equal to one-tenth the load. This assumes that the road is smooth and hard and that friction may be neglected.

115. The Screw.

The thread of a screw is an inclined plane which winds spirally about an axis. The length of the thread is the length of the inclined plane and the length of the screw is the height of the inclined plane. The thread may be considered the hypotenuse of a right-angled triangle wrapped about an axis. This may be made clear by cutting paper in the form of such a triangle and wrapping it about a pencil. The distance between two adjacent threads measured parallel to the axis, is called the *pitch* of the screw.

FIG. 74.



The screw.

The threads of the screw are made to fit into corresponding spiral grooves in a nut.

When the screw is turned once around it advances a distance equal to the pitch of the screw.

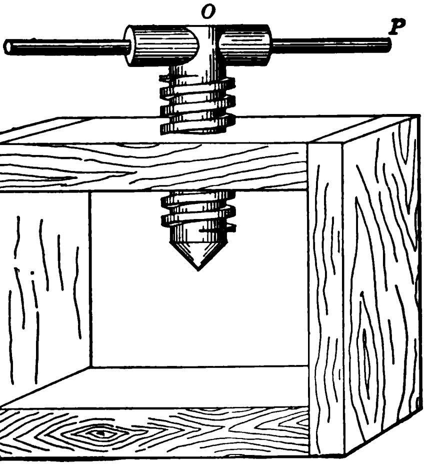
The mechanical advantage, then, is the ratio of the pitch to the length of the thread required to pass once around the screw.

116. Uses of the Screw.

All are familiar with the letter press, the hoisting jack, and many other machines in which the principle of the screw is applied.

In most cases a lever is attached to the head of the screw, thus forming a compound machine and greatly increasing the mechanical advantage, as shown in the figure.

FIG. 75.



Use of the screw.

Let P in Fig. 75 be a point at the end of a lever where force is applied to turn the screw. When P moves once around a circle whose radius is *OP*, the screw advances a distance equal to its pitch.

Applying the general law of machines, we have

P × *circumference through which it moves* = *R* × *pitch of screw*, where *R* is the resistance at the point of the screw.

Suppose the force is 25 pounds, the length of the lever 18 inches, and the pitch $\frac{1}{8}$ inch.

Substituting in the equation above and remembering that the circumference of a circle is $2\pi r$,

$$\begin{aligned} 25 \times 2 \times 3.1416 \times 18 &= \mathrm{R} \times \tfrac{1}{8} \\ \therefore \mathrm{R} &= 22{,}619.6 \text{ pounds.} \end{aligned}$$

By exerting a force of 25 pounds at the end of the lever, a resistance of over 11 tons can be overcome at the end of the screw.

The friction, however, is considerable in a machine of this kind, so that the resistance which could be actually overcome is not so great.

117. Friction.

In all the machines just described, the theoretical advantage only has been considered. In practice, however, friction plays an important part.

No surface can be made perfectly smooth, and so when one body is made to slide upon another, there will be a certain amount of resistance caused by friction.

Experiment 18.

Prepare a block 2 × 4 × 6 inches. Plane its surfaces and slightly round the sharp edges. Place it upon a large sheet of paper. Attach a thread to the block and to the hook of the spring scales. Pull upon the scales and drag the block with uniform motion over the paper, noting the position of the index on the scales. Try different velocities, and it should be found that the amount of friction is not sensibly changed by a change in velocity.

Try the block on its side and on its edge. The friction is the same in either case.

Try various weights upon the block. The friction will vary as the weight.

118. Laws of Friction.

Conclusions from such experiments as are described above are as follows:

Friction does not depend on the rate with which one surface slides upon another.

Friction does not depend upon the area of the surfaces in contact.

Friction is proportional to pressure between the surfaces in contact.

119. Coefficient of Friction.

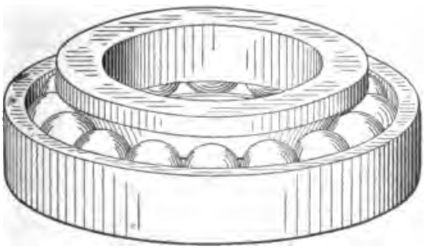
The ratio between the force required to overcome friction, and the pressure between the surfaces in contact, is called the *coefficient of friction.* If, for example, a box weighing 200 pounds is dragged along the floor with a force of 40 pounds, the coefficient of friction is $\frac{1}{5}$.

120. Methods of avoiding Friction.

The bearings of machines are made true and smooth and are constantly lubricated to lessen the friction. Good lubricating oil will greatly increase the efficiency of a machine. That is, the machine will transfer more of its energy when but little is expended in overcoming friction and producing heat.

Ball bearings are extensively used to decrease friction. As shown in Fig. 76, the axle of a rotating wheel is surrounded by a number of very hard steel balls which rotate as the axle turns.

FIG. 76.



Ball-bearing.

In some cases, however, friction is very desirable. The brakes used on wagons and cars would be of no use if there were no friction between the brake and the wheel. The smooth ice presents a very desirable surface to one who wishes to skate, but ice on a pavement or street interferes with travel and traffic.

Problems.

1. A lever is 15 feet long. The fulcrum is placed so that the force-arm is 15 feet long and the resistance-arm is 4 feet long. What resistance will a force of 50 kg. balance? *Ans.* 187.5 kg.

2. In a lever of the third class it is found that the resistance moves through 20 cm. when the force moves 3 cm. What force will balance 25 g.? *Ans.* $166\frac{2}{3}$ g.

3. A uniform stick 100 cm. long weighs 200 g. The fulcrum is placed 20 cm. from one end. What weight suspended from the end of the long arm will balance a mass of 500 g. suspended from the end of the short arm? *Ans.* 50 g.

4. A beam 10 feet long, uniform in shape and density, weighing 800 pounds, is supported by a prop at each end. A weight of one ton is hung from the beam 4 feet from one end. How much weight rests on the props? *Ans.* 1200 and 1600 pounds.

5. A wheel-barrow is 8 feet long from the end of the handles to the axle of the wheel. A weight of 500 pounds is placed half way between these points. What force applied at the end of the handles will lift the weights? *Ans.* 250 pounds.

6. A compound lever is composed of three single levers of the first class. The long arms are 20, 30, and 50 cm. long, and the short arms are 2, 3, and 10 cm. long respectively. What is the greatest resistance that may be overcome by the system by the application of a force of 45 g.? *Ans.* 22.5 kg.

7. Four movable pulleys are arranged as in Fig. 66. What will be the mechanical advantage? *Ans.* 1 : 8.

8. A windlass (§ 112) is used to lift from a well a weight of 200 pounds. The force employed is 25 pounds and the axle is 2 inches in diameter. How long must the handle be? *Ans.* 8 inches.

9. If the wheel (§ 113) is 70 cm. in diameter and the axle is 3 cm. in radius, what force will be required to overcome a resistance of 750 pounds. The force to be applied to the rim of the wheel and the cable to pass over a pulley as shown in Fig. 69? *Ans.* 32.143 pounds.

10. An inclined plane rises 1 m. in 40 m. A wagon and its contents weigh 3000 pounds. What force must be exerted to prevent the wagon running down the grade? Solve by both the graphical and the geometric method. *Ans.* 75 pounds.

11. A skid 8 feet long is placed with one end on the ground and the other upon a platform 4 feet high. What force must be exerted parallel to the ground to roll a barrel weighing 296 pounds on to the platform? *Ans.* 170.9 pounds.

12. If the pitch of a screw is 3 mm. and the handle of the lever through the head of the screw extends 50 cm. to each side, what is the mechanical advantage? *Ans.* 1 : 1047.2

13. A large cogwheel is made to turn a small one. The large one contains 100 teeth and the small one 8 teeth. When the large one is rotated 50 times a minute, what is the speed of the small one? *Ans.* 625 rotations per min.

14. A belt runs from a flywheel to a pulley. The pulley is 10 inches in diameter and makes 2000 rotations per minute. The flywheel rotates 200 times per minute. What is the diameter of the flywheel? *Ans.* 8⅓ feet.

CHAPTER IX.

MECHANICS.

LIQUIDS.

121. Nature of a Liquid.

A *fluid* is any substance that will flow. Both liquids and gases are fluids.

In this chapter the mechanics of liquids will be discussed, and in the next chapter, that of gases.

The molecules of a liquid may easily glide by one another and, consequently, liquids are not rigid like solids.

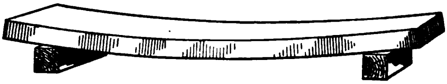
A liquid offers no resistance to a change of form. Its shape is that of the vessel in which it is contained.

122. Viscosity.

Some substances partake of the nature of both liquids and solids. They will, when under continued stress, slowly change their shape. This property is called *viscosity* and the substance is said to be *viscous*.

Asphaltum, a substance often used in paving streets, is a good example of a viscous substance. It is quite brittle and may easily be chipped off with a knife, but if a block of it be set aside for a few days, it will be found to have slowly sunk down and spread out.

FIG. 77.



A slab of ice.

Ice is also viscous, as may be shown by supporting a long slab of it at the two ends. In course of a day the slab will be permanently changed in shape by the force of gravity acting upon it.

Thick molasses is viscous and when poured out upon a plate will heap up and then slowly spread out.

Various substances have different degrees of viscosity, all the way from thin liquids to rigid solids.

123. Surface Tension.

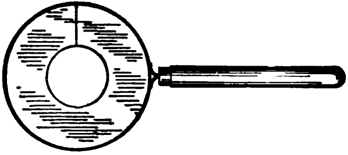
A thin elastic film appears to be stretched over the free surface of liquids. The film is of the same material as the rest of the liquid, but its behavior is different. The molecules in the body of the liquid cohere to other molecules which are about them on all sides, but the molecules at the surface are attracted only by those below them and at their sides. This causes a tension out in all directions from any point on the surface. Hence the name *surface tension.*

Experiment 19.

Prepare a loop of wire three or four inches in diameter, as shown in Fig. 78. Tie to one side of it a loop of thread. Dip all into a good soap solution and lift off a film.

Break the part of the film within the loop of thread by touching it with the point of a pencil or, better, with a hot metal point. The thread will at once take the form of a perfect circle, because the tension of the film is equal in all directions.

FIG. 78.



Tension of soap film.

The soap film has two free surfaces and hence there is surface tension on both sides.

Experiment 20.

Wet a piece of clean glass on one side and place it horizontally. Let a drop of alcohol fall upon the center of the glass. The film of water will draw away from the alcohol in all directions.

The surface tension of alcohol is much less than that of water, and so the film on the surface of the water was broken by the drop of alcohol much as the film within the loop of thread was broken in the experiment above.

Experiment 21.

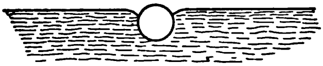
Split a light pine stick at one end and insert a small piece of gum camphor. Place it upon water in a large vessel. The stick will be drawn about on the surface of the water.

The camphor breaks the water film in the rear of the stick and the surface tension then draws the stick about with it.

Experiment 22.

Place a needle upon the end of a slip of stiff paper and hold it near and parallel to the surface of water. Tilt the paper and roll the needle on to the surface of the water. The needle will float and will make a depression on the surface just as if the water were covered with a thin membrane, or, as it is sometimes called, a "water skin." The needle is supported by the buoyancy of the water and the surface tension.

FIG. 79.



Section, showing needle on water.

124. Shape of Drops of a Liquid.

When a body of liquid is free from outside forces, it becomes spherical in shape. The surface is constantly under tension and a sphere has a smaller surface than any form of the same volume.

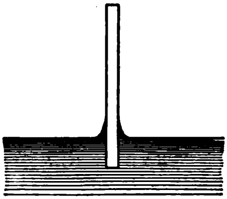
For this reason rain drops are nearly spherical while falling.

Advantage is taken of this principle in the manufacture of shot; melted lead is separated into fine drops and allowed to fall through a distance such that they will cool and harden while in the spherical form.

125. Capillarity.

When a plate of glass is dipped into water the water will adhere to it and rise on both sides as shown in Fig. 80. This will occur in case of any liquid or solid when the liquid adheres to the solid more strongly than it coheres to its own molecules that is, whenever the liquid wets the solid.

FIG. 80.

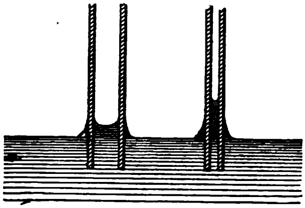


Glass plate in water.

When a capillary tube is used, the water adheres to the inner walls and climbs up the sides. The surface tension is strong enough to raise the water to a considerable height in the tube. The smaller the bore of the tube is, the higher the liquid will rise.

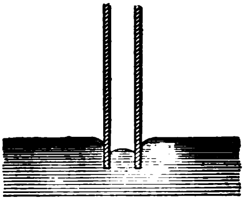
In the case of a liquid in which the cohesion between its molecules is greater than the adhesion to a solid, the liquid will be depressed instead of raised. This may be illustrated by thrusting a capillary glass tube into mercury, as shown in Fig. 82. The rules of capillary attraction may be stated as follows:

FIG. 81.



Capillary tubes in water.

FIG. 82.



Capillary tubes in mercury.

(1) *Liquids are raised in a capillary tube which they wet, and are depressed when they do not wet it.*

(2) *The rise or depression is inversely proportional to the size of the bore of the tube.*

(3) *Heat diminishes the capillary action.*

126. Some Uses of Capillarity.

In nature and in the arts there are numerous instances of capillary action. If a piece of soft wood is placed upright with one end in water, it will be found after a time that the wood is water-soaked for a considerable distance above the level of the water.

The rise of sap in plants is greatly assisted by capillary action.

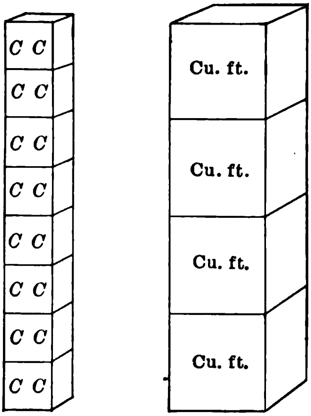
Ink is soaked up by a blotter and oil rises in a lamp-wick by capillary action.

Frequently this action is an inconvenience, as when moisture creeps through the ground into cellars, or when it soaks through brick walls.

127. Liquid Pressure due to Gravity.

A cubic centimeter of pure water at 4° C., its greatest density, weighs 1 g. A cubic foot of water under the same conditions weighs 62.424 pounds. If we imagine eight cubes of water piled one on top of another, as in Fig. 83, each 1 c.c., the pressure at the bottom will plainly be the sum of the weights of all, or 8 g., on a square centimeter.

FIG. 83.



Liquid pressure.

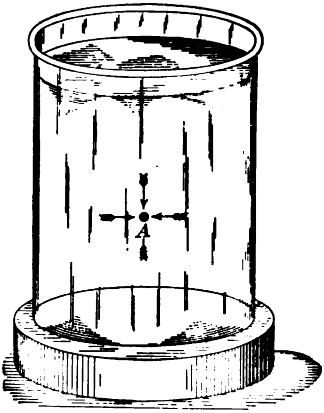
In case of the cubic feet, the pressure on the bottom would be the weight of one cube multiplied by the number of them. In this case, as shown in Fig. 83, 62.424 × 4 = 249.696 pounds on a square foot.

The pressure at the bottom of any one of the cubes is equal to the sum of the weights of the cubes above it.

128. Pressure at any Point Equal in all Directions.

At any point in a still liquid the pressure is equal in all directions—upward, downward, and sideways. This will be plain from a consideration of any point in a liquid, as *A* in Fig. 84. The least force will produce motion in a liquid. If, then, the pressure at the point *A* were not equal in all directions, the water there would be set in motion.

Fig. 84.

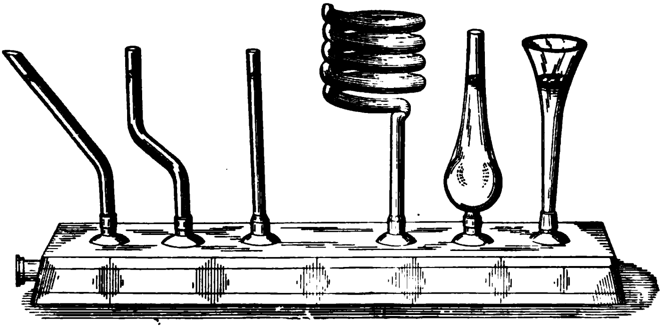


Pressure at any point equal in all directions.

129. Pressure Independent of the Shape of the Vessel.

The pressure of any given liquid upon the bottom of a vessel depends upon the depth of the liquid only. The shape of the vessel does not affect the pressure. This is shown in Fig. 85, where all the vessels communicate with the water in the base and the water stands at the same height in all. Each must then exert the same downward pressure notwithstanding the fact that the shapes of the vessels are different. Otherwise, the liquid would flow from one to the other. This principle may be demonstrated by the following experiment.

Fig. 85.

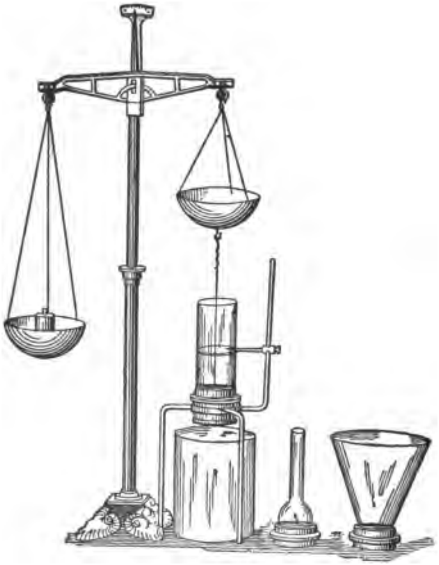


Pressure proportional to depth.

Experiment 23.

Three glass vessels are provided, having shapes shown in Fig. 86. All have a base of the same area. The base is movable and is attached by a cord to one arm of a balance. It is held against the base of the vessel by a suitable weight in the scale pan.

FIG. 86.



Pressure dependent on depth.

Water is then poured into the vessel until the bottom is pushed off. The height of the water is marked by a pointer.

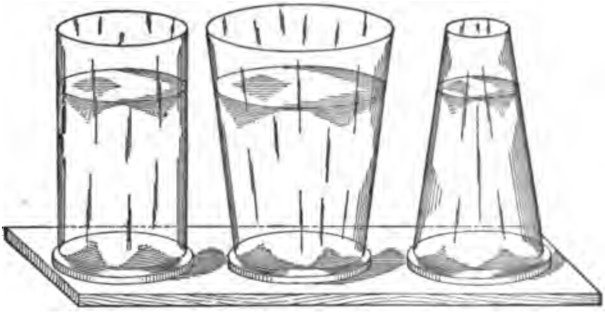
This vessel is then removed and the others in turn are put in its place. It is found that the depth of water necessary to balance the weight will be the same in all cases.

130. To calculate Pressure on the Bottom of a Vessel.

To calculate the pressure upon the bottom of a vessel, when gravity alone is considered, it is necessary to know only *the area of the bottom, the depth of the liquid, and the weight of the unit volume of the liquid.*

Suppose the base of a vessel has an area of 35 sq. cm. and the vertical distance from the surface of the liquid to the base is 125 cm. The volume of such a column of liquid is 4375 c.c. If the liquid is water, each cubic centimeter weighs 1 g. Hence the pressure on the bottom is 4375 g.

FIG. 87.



Hydrostatic paradox.

If the liquid is mercury, each cubic centimeter weighs 13.6 g., and the pressure on the bottom is 59,500 g.

The actual weight of the liquid may be more, less, or the same as the pressure on the bottom, as illustrated in Fig. 87.

In all three cases the pressure on the bottom is calculated in the manner described above.

131. To calculate the Pressure on the Sides of a Vessel.

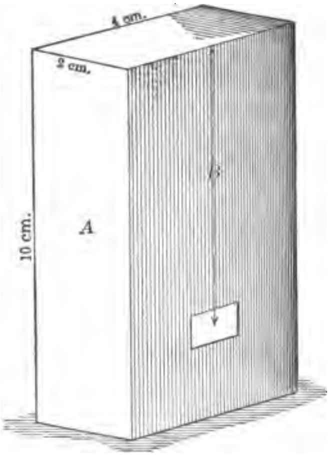
Suppose it is desired to know the pressure on the side *A*, Fig. 88, when the vessel is filled with water. Let the side be vertical, and the dimensions of the vessel, 2 × 4 × 10 cm. The area of the side *A* is then 20 sq. cm. The pressure against the side increases with the depth. At the surface it is nothing and at the bottom it is maximum. Therefore the average pressure against the side would be half the sum of the pressure at the top and bottom. This would be the pressure at a point midway between. Consequently *the pressure against the side is equal to the weight of a column of* *liquid whose base is equal to the area of the side and whose height is equal to one-half the depth of the liquid.*

If the vessel in Fig. 88 is filled with water, the pressure on *A* is the weight of a column of water 2 × 10 × 5 cm., or 100 g.

If it is desired to know the pressure on any part of one side, the small square on the side *B*, for example, the average depth is the distance from the surface to the middle of the part considered.

Let the area of the small square be 2 × 2 cm. and the distance from the surface of the liquid to the middle of the square, 8 cm. The pressure against the square is then the weight of a column of water 8 × 2 × 2 cm., or 32 g.

FIG. 88.



Pressure on the interior of a vessel.

The total pressure on the interior of a vessel is evidently the sum of the pressures on the sides and bottom.

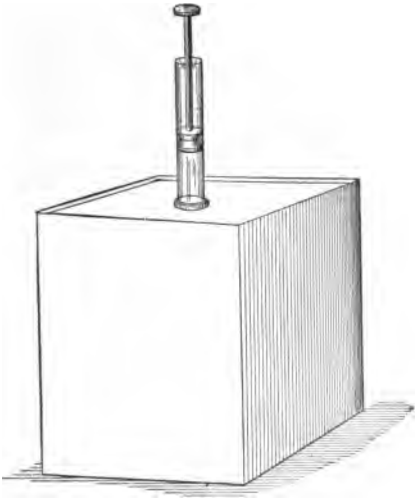
132. Transmission of Pressure in Liquids.

When a liquid is enclosed in a vessel and pressure is applied to any part of it, this pressure is at once transmitted to all parts of the interior of the vessel. This principle is concisely stated in Pascal's Law, as follows:

The pressure applied to any given area of a liquid enclosed in a vessel, is transmitted to every equal area on the interior of the vessel.

If, in Fig. 89, the area of the piston is 5 sq. cm. and a pressure of 50 g. is exerted downward on the handle, this pressure will be transmitted to every area of 5 sq. cm. whether on the bottom, top, or sides of the vessel.

FIG. 89.

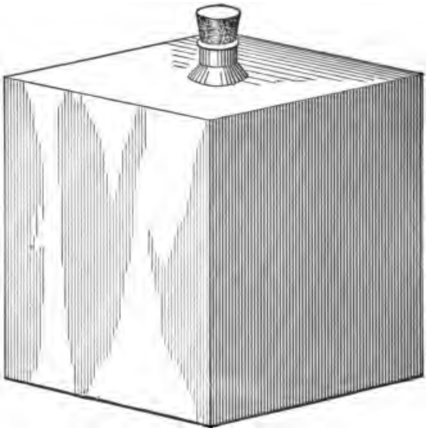


Illustrating Pascal's principle.

Suppose we have a cubical vessel such as is shown in Fig. 90, each edge being 10 cm. The hole in the top is 2 cm. in diameter. The vessel is filled with water and a cork is pressed into the hole with a force of 100 g. If the diameter of the cork is 2 cm., the area of water exposed to pressure is 3.1416 sq. cm. The total area of the cube is 600 sq. cm. The number of areas as large as the hole is nearly 191. Therefore the total pressure on the interior of the vessel, due to the pressure on the cork, is $191 \times 100 = 19{,}100$ g.

The use of liquids of different density, mercury for example, does not change the result in this case.

FIG. 90.



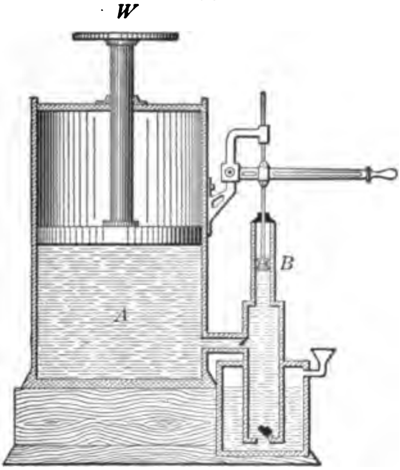
Pressure on interior of a vessel due to outside pressure.

When the total pressure due both to gravity and external pressure is desired, each may be found separately and the results added.

133. Hydraulic Press.

The hydraulic press is a practical application of Pascal's Law. In this machine there are two communicating chambers, *A* and *B*, Fig. 91. Each chamber is a cylinder which is fitted with a piston. *B* is, in fact, a force pump and, by its operation, liquid is forced into the chamber *A*. The area of the piston in *A* is always much larger than that in *B*. Suppose their areas are in the ratio of 1: 500. Then, since any pressure on the small piston is transmitted to every equal area on the large one, the force will be multiplied 500 times because of the difference in area of pistons. If, in addition, the force be applied at the end of a handle whose force-arm is five times as long as the resistance-arm, this again will multiply the force five times. The total gain in force by this arrangement would be 1 : 2500.

Fig. 91.



The hydrostatic press.

If a force of 100 pounds is applied at the end of the lever, the enormous force of 125 tons will be exerted at *W*.

The piston in *A*, of course, moves very slowly, for the loss in speed or distance is in proportion to the gain in force (§ 103).

This machine is extensively used where a large force is desired, as in lifting ships or buildings, pressing car-wheels upon their axles, pressing cotton into bales, and in many other ways.

134. Buoyancy.

The force which tends to raise bodies to the surface of a fluid is called *buoyancy.*

As a result of buoyancy, a balloon ascends, hot air rises in a chimney, wood floats on water, and iron floats on mercury.

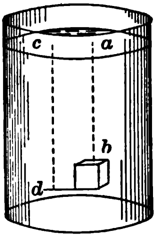
Not all bodies will rise in the fluid in which they are placed, but the buoyancy is just as great whether the body sinks or floats, as long as the volumes of the bodies are the same.

The reason some bodies sink in liquids or gases is because the force of gravity directed downward is greater than the force of buoyancy directed upward.

135. Cause of Buoyancy.

To understand buoyancy it is necessary to consider two principles which have already been explained, — (1) *pressure in a fluid increases with the depth* and (2) *at any point the pressure is equal in all directions.*

FIG. 92.



Buoyancy.

Keeping these two principles in mind, it is plain that the block in Fig. 92 is pressed upon the top by a column of liquid whose depth is *ab*, while the pressure on the bottom of the block is due to the weight of a similar column whose depth is *cd*. The pressure downward on the top of the block is not as great as the pressure upward on the bottom, because the bottom is deeper in the liquid.

Suppose the block is a cube, 2 cm. along one edge. Its volume is then 8 c.c. and the surface area of each face is 4 sq. cm. Let the top of the block be 10 cm. below the surface of the water. Then the column of water resting on top of the block is $2 \times 2 \times 10$ cm. $= 40$ c.c. and weighs 40 g.

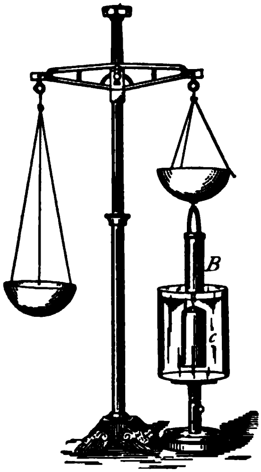
The column pressing upwards on the bottom is $2 \times 2 \times 12$ cm. $= 48$ c.c. and weighs 48 g.

The difference between these two forces shows that there is an unbalanced force of 8 g. directed upwards. The volume of the block is 8 c.c., so that the buoyancy is just equal to the weight of the water displaced by the block.

Experiment 24.

Suspend from one arm of a balance a brass bucket, *B*. From a hook below it suspend a closed brass cylinder which fits into and fills the bucket. Balance the beam with weights in the pan. Now place a vessel of water so that the cylinder *c* is just submerged. The equilibrium will be destroyed by the buoyancy of the water. Fill the bucket *B* with water and the equilibrium will be restored. This shows that the cylinder was buoyed up by a force equal to the weight of the water which it displaced, for it just fills the bucket and, of course, will occupy the same space when immersed in the water.

FIG. 93.



Principle of Archimedes.

136. The Principle of Archimedes.

The experiment just described was first made by Archimedes. The principle involved may be concisely stated as follows:

A body immersed in a fluid is buoyed up by a force equal to the weight of the fluid displaced.

If 500 c.c. of iron weighs 3500 g., its apparent weight in water is 3000 g., because 500 c.c. of water weighs 500 g. Hence the buoyancy, according to Archimedes' principle, is 500 g.

Numerous illustrations of this principle may be observed on every hand.

A boat, a cork, or a board, will float on water but will sink just far enough to displace a volume of water equal in weight to the weight of the floating body.

A body will sink whenever its weight is greater than the weight of its volume of the fluid in which it is immersed.

A balloon will ascend whenever the air which it displaces weighs more than the balloon.

When a body's weight is equal to the weight of the same volume of a liquid, the body will neither sink nor float but will remain in any position where it may be placed. This is very nearly the case with the human body when immersed in water. One who can swim with only his nose out of water, will need to make very little effort to keep himself afloat.

137. Density.

The density of any substance is the amount of matter in the unit of volume. For example, the density of water is 1 g. per c.c; mercury, 13.6 g. per c.c; cork, .24 g. per c.c.

If the English units are employed, we may say that the density of water is 62.42 pounds per cubic foot; mercury, 848.9 pounds per cubic foot.

When the density of any substance is known, the weight of any given volume of it may easily be determined. For example, a sandstone measures 100 × 50 × 50 cm. The density of the stone is 4 g. per c.c. The weight of the whole stone is then the volume in cubic centimeters mutiplied by the weight of 1 c.c. Hence,

$$100 \times 50 \times 50 \times 4 = 1000 \text{ kg.}$$

On the other hand, the density of any body may be found by dividing its weight by its volume.

138. Specific Gravity.

The specific gravity of a substance is the ratio of its weight to the weight of an equal volume of a standard substance.

The standard substance for solids and liquids is pure water at the temperature of its greatest density (4° C).

It must be clearly understood that specific gravity is a *ratio.* It is simply a *number* which is obtained by dividing the weight of any substance by the weight of an equal volume of water.

Since the weight of a cubic centimeter of water is 1 g., the density and specific gravity of a substance are expressed by the same number when the metric units are used. Such is not the case when English units are used.

139. Determination of Specific Gravity.

There are many ways of determining the specific gravity of substances, but in all the methods the aim is to find two things: (1) *The weight of a body.* (2) *The weight of an equal volume of water.*

The ratio of these two numbers is the specific gravity.

$$\text{Specific gravity} = \frac{\text{weight of body}}{\text{weight of equal volume of water.}}$$

140. To find the Specific Gravity of a Solid that will sink in Water.

If a solid, such as iron, lead, or stone, is first *weighed in air,* then suspended by a fine thread and weighed in water, the difference between these two weights is the *weight of an equal volume of water* (§ 136).

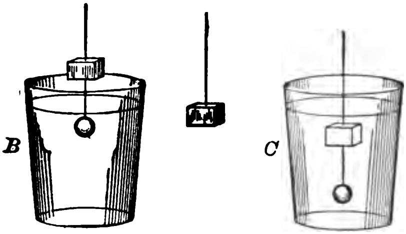
For example, a body of lead weighs 33.9 g. in air, and 30.9 g. in water. The loss of weight in water is 3 g. Hence,

$$\text{Specific gravity of lead} = \frac{33.9}{3} = 11.3.$$

141. To find the Specific Gravity of a Solid that Floats on Water.

When the density of a body is less than that of water, it may be submerged by attaching to it a sinker of some heavy material, such as lead. The body is first weighed in air. Then the sinker is attached to it and the weight of both taken while the sinker only is in the water, as shown in *B*, Fig. 94. Next, both are submerged as in *C*. It is plain that since the sinker was in the water in both *B* and *C*, the difference in the weights is only the buoyancy of the water on the body. This is the weight of a volume of water equal to that of the body. We now have the *weight of the body* and the *weight of an equal volume of water.*

Fig. 94.



To find specific gravity of a body lighter than the same volume of water.

The division of the former by the latter gives the specific gravity.

142. To find the Specific Gravity of a Solid by Immersion in a Liquid Other than Water.

It is sometimes desirable to find the specific gravity of a solid in reference to some other liquid of known density. If this number is then multiplied by the specific gravity of the liquid, the ratio to the density of water will be determined.

For example, a mass of iron weighs 70 g. in air and 62 g. in alcohol. The weight of a volume of alcohol equal to that of the iron is then 8 g.

$$70 \div 8 = 8.75.$$

That is, iron is 8.75 times as heavy as the same volume of alcohol.

But alcohol is known to be only .8 as dense as water and consequently 8.75 is $\frac{10}{8}$ of the specific gravity. The specific gravity of the iron, therefore, is

$$\frac{70}{8} \times .8 = 7.$$

In all such cases, proceed as though the liquid were water and then multiply by the specific gravity of the liquid.

143. To find Specific Gravity of a Liquid by Immersion of a Solid in it and in Water.

In liquids as in solids the whole operation consists in finding the weights of equal volumes of two substances, one of which is water, and then dividing by the weight of the water.

If a solid is immersed in water, the difference between its weight in water and in air is the weight of the water displaced.

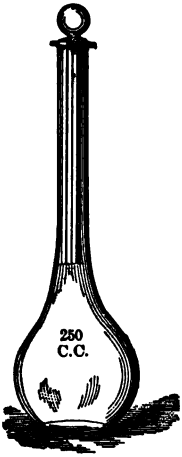
If then it be weighed in another liquid, the difference between its weight there and in air would be the weight of the liquid displaced.

The volume of the water and liquid displaced are of course equal. The quotient of the latter by the former is the specific gravity of the liquid.

144. The Specific Gravity Bottle.

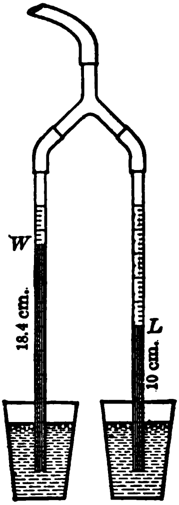
The specific gravity of liquids may often be most conveniently determined by use of a bottle such as is shown in Fig. 95. The neck is small and marked with a ring to which the bottle is to be filled. The weight of pure water which the bottle will hold when filled up to the mark, is determined once for all and marked on the bottle. If at any time the bottle is filled in the same way with any other liquid and weighed, the specific gravity is readily determined.

FIG. 95.



Specific gravity bottle.

FIG. 96.



To find density of liquids.

145. Specific Gravity by Balancing Columns.

When two columns of liquids are raised by equal forces, their height is inversely proportional to their densities. The lighter liquid will rise higher (§ 129).

Two glass tubes (Fig. 96) are connected to a three-way tube at the top. The lower end of one is inserted into a vessel of water, and the lower end of the other into a vessel containing the liquid whose specific gravity is to be determined.

If some air is withdrawn at the top, the liquids are raised by the same atmospheric pressure to a height inversely proportional to their densities.

Suppose the water rises to *W*, Fig. 96, and sulphuric acid in the other vessel rises to *L*. Then

D (water) : D (sulphuric acid) = 10 : 18.4.

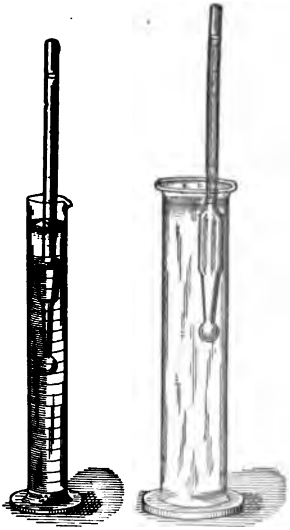
∴ Density, or specific gravity, of sulphuric acid = 1.84.

146. Hydrometers.

The most convenient method of finding the specific gravity of liquids is by use of a hydrometer. This instrument is made of glass and is loaded with lead or mercury at its lower end so that it will float in an upright position.

The principle of a hydrometer is this: Any body that floats will sink until it displaces a volume of water equal in weight to its own weight. Of course, then, the lighter the liquid the deeper the floating body will sink into it. The depth to which the body will sink is inversely proportional to the density of the liquid.

FIG. 97.



Hydrometers.

The hydrometer is a floating body, and when it is placed in water it will sink to the zero mark on the stem. The one for liquids heavier than water has the zero mark near the top of the stem. When it is placed in a heavier liquid it is raised and the specific gravity can be read directly from the marks at the surface of the liquid.

The one for liquids lighter than water has the zero near the bottom of the stem. When placed in a lighter liquid it will sink in proportion to the density.

When the first, for example, is placed in sulphuric acid, it will rise to about 1.84. When the second is placed in alcohol, it will sink to about .8. These figures indicate the specific gravity of these liquids.

Problems.

1. What is the pressure per square inch at the bottom of a lake 100 feet deep? *Ans.* 43.34 pounds.

2. What is the pressure per square centimeter at the bottom of mercury 35 cm. deep? *Ans.* 476 g.

3. A stand pipe 50 feet high is filled with water. What is the lateral pressure at a point half way down from the top? (§ 128)
Ans. 1560.5 pounds per square foot.

4. A rectangular tank measures 6 × 10 × 20 cm, and stands on one end. Find the total pressure on the bottom and on the smaller side when the tank is filled with water. *Ans.* 1200 g. on bottom.
1200 g. on smaller side.

5. Find the total pressure on the interior of a cylinder 20 cm. in diameter and 50 cm. high, when filled with mercury.
Ans. 1281.8 kg.

6. A cubical vessel 8 cm. on an edge, has a tube extending from the top to a height of 30 cm. When cube and tube are filled with water what is the pressure on the bottom and on one side of the cube?
Ans. 2432 g. on bottom.
2176 g. on one side.

7. The top of a closed vessel filled with water is 10 × 20 cm. A hole in the top is 3 cm. in diameter. A cork in the hole is pressed against the water with a force of 100 g. What is the total pressure on the top including the cork? *Ans.* 2829.4 g.

8. The diameter of the large piston of a hydraulic press is 40 cm. and the area of the piston of the pump is 3 sq. cm. What is the ratio of gain in force when the force-arm is five times as long as the resistance-arm? *Ans.* 1 : 2094.4.

9. What is the difference of pressure on the top and bottom of a 3 cm. cube when immersed in water? *Ans.* 27 g.

10. How much less will 740 grams of cast iron weigh when it is immersed in water? *Ans.* 100 g.

11. What is the density of a piece of cast iron which is 2 × 3 × 5 cm. in dimensions, and weighs 234 g.? *Ans.* 7.8 g. per c.c.

12. A piece of cast iron weighs 234 g. in air and 204 g. when immersed in water. What is its specific gravity? *Ans.* 7.8.

13. A block of wood weighs 20 g. in air. When a sinker, immersed in water, is suspended from it, the two weigh 35 g. When both sinker

and block are in water, the weight is 15 g. Find specific gravity of the wood. *Ans.* 1.

14. A piece of lead weighs 450 g. in air, and in sulphuric acid 376.73 g. Find specific gravity of the lead. *Ans.* 11.3.

15. A body weighs 17 g. less in water than in air. In another liquid, 22 g. less. Find the specific gravity of the liquid. *Ans.* 1.294.

16. A 25 c.c. bottle holds 340 g. of mercury. Find specific gravity of the mercury. *Ans.* 13.6

17. A column of water 75 cm. high is balanced by a column of another liquid 60 cm. high. Find specific gravity of the liquid. *Ans.* 1.25.

18. What is the weight of a solid brass sphere 25 cm. in diameter. *Ans.* 69.54 kg.

19. (This is an extra problem for those who would like to work it out.) The story goes that King Hiero supplied a quantity of gold and silver to a goldsmith and asked him to make of it a crown. The smith melted the metals together, forming an alloy, and made the crown as directed. The king afterward suspected that some of the gold had been kept out and silver put in its place. He appealed to Archimedes to determine the amount of each metal in the crown. How would he do it?

He found the weight of the crown in our notation, to be 384 g., and its specific gravity 18. He also knew that the volume of any substance is equal to its mass divided by its density, thus making the volume of the crown 21.33 c.c. He knew that the density of silver is 10.5 g. per c.c., and gold 19.3 g. per c.c.

Now if he would let x equal the mass of silver, $384 - x$ would be the mass of gold. What equation can you now form from which the value of x may be determined? *Ans.* Gold, 351 g.; silver, 33 g.

CHAPTER X.

MECHANICS.

GASES.

147. Gases.

Fluids include both liquids and gases.

Under proper conditions of temperature and pressure, any liquid may be converted into a gas or a gas into a liquid. Some properties are common to all fluids, but gases differ from liquids in several important particulars.

When matter is in a gaseous form, the molecules no longer cohere, as in liquids and solids, but are repelled from each other and distribute themselves equally throughout the space in which they are enclosed. If a cubic centimeter of a gas, for example, is placed in a closed vessel whose capacity is one liter, the molecules will move away from each other until the whole space is filled. Their distance apart, of course, is then much greater.

Gases can be made to occupy a limited space only by enclosing them on all sides. The enclosure may be the walls of a vessel or it may be outside forces pressing in on all sides. A cubic foot of air continues to contain about the same number of molecules, because the air-pressure on all sides prevents its expansion.

148. Air.

Air is the most abundant of all gases, and the phenomena resulting from air-pressure forms the chief subject of this chapter.

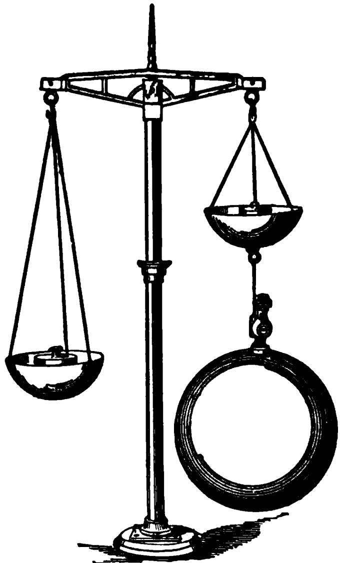
The great body of air which surrounds the earth is called the atmosphere. It is a part of the earth and rotates upon the axis along with the solid and liquid parts. Since air is matter it is attracted by the force of gravity and, consequently, it cannot expand and escape into the space beyond. No definite height can be assigned to the atmosphere. Its density grows less and less as we ascend, until a point is reached where there is no air. If the air were all as dense as it is at sea-level, it would all be included within a height of five miles. As it is, the total height may be one thousand miles.

149. Weight of Air.

The density of air is small as compared with that of water, being about in the ratio of 1 : 773; *i.e.* a liter of air under standard conditions of temperature and pressure weighs only $\frac{1}{773}$ as much as the same volume of water.

That air has weight, may be shown by the following experiment.

FIG. 98.



Weight of air.

Experiment 25.

A brass globe about 20 cm. in diameter and provided with a stopcock is suspended from one arm of a balance, as shown in Fig. 98.

Weights are placed in the pan of the other arm to balance the globe. The air is then removed from the globe as completely as can be done by an air pump or aspirator. The balance will then be disturbed. Take weights from the pan until equilibrium is again secured. Admit air by opening the stopcock, and equilibrium will again be destroyed.

Careful experiments show that one liter of air under a pressure of 76 cm. of mercury and at the temperature of melting ice weighs 1.293 g. One cubic foot of air under the same conditions weighs about 1.28 ounces.

When pressure is removed or temperature is raised, the air will expand and consequently the density will diminish.

The air in a room 50 × 40 × 15 feet weighs, under ordinary conditions, nearly one ton.

150. Air-Pressure.

The pressure of the air at sea-level is about 1033.6 g. per square centimeter or 14.7 pounds per square inch. The force of gravity which causes the pressure in water, is also the cause of air-pressure. The weight of all the upper strata of air rests upon the air below, so that air next to the ground is pressed upon by the weight of all above it.

The air, like all gases, is very compressible. For this reason the density of air at sea-level is much greater than it is in the higher regions.

The pressure of 14.7 pounds per square inch, or 1033.6 g. per square centimeter, is called *one atmosphere.*

151. Buoyancy in Air.

Since pressure in the lower strata of air is greater than in the higher, and since, also, the pressure at any point in a fluid in equilibrium is equal in all directions, it follows that when any body is immersed in air it will be pressed upward on the bottom with greater force than it is pressed downward on the top. This difference of pressure is the buoyancy of the air. The amount of buoyancy is equal to the weight of the air displaced. When objects are small and dense, the difference in their weight in air and in a vacuum is very slight. In delicate weighing, however, allowance must be made for buoyancy.

When a mass of cork or other light material is placed in one pan of a balance, and an equal mass of lead in the other pan, the lead will appear to be heavier because of the greater buoyancy of air on the cork. It will require more than one pound of the cork to balance a pound of the lead.

When a body is very light, the buoyancy of the air may be greater than the weight of the body. In this case the body will ascend.

All balloons operate on this principle. A balloon fifty feet in diameter will displace more than two and one-half tons of air. This, then, is the upward force on the balloon. If the weight of the balloon is less than this amount, there will be a greater force acting upward than downward, and as motion is always in the direction of the greater force, the balloon will ascend.

Balloons are filled with a light gas such as hydrogen. It would be better if they were perfectly empty, but the hydrogen is necessary to equalize the pressure of the air on the outside. If the walls of a balloon were made strong enough to resist air-pressure, the weight would be much greater than the buoyancy.

A balloon will ascend until the buoyancy is equal to its weight and it will there be in equilibrium except in so far as the winds may blow it about at that level.

Water has nearly the same density at the surface as at great depths, so that its buoyancy will cause light objects to float on its surface. In air, however, the density rapidly decreases as the height above the earth increases, so that a balloon cannot be constructed which will rise to the surface of the atmosphere.

Balloon ascensions have been made to a height of seven miles.

152. Ventilation.

Ventilation is a process of changing the air in any room or other enclosure. This is accomplished chiefly by the principle of buoyancy explained above. When the air in a chimney or air-shaft is warmed it becomes lighter than air outside and will ascend for exactly the same reason that a balloon ascends.

This subject is discussed more fully in the next chapter, under the subject of heat.

153. Some Illustrations of Atmospheric Pressure.

We are so accustomed to the pressure of the atmosphere that we are scarcely conscious that it exists. At all places where it requires a column of mercury thirty inches high to balance the atmospheric pressure, the pressure must be 14.7 pounds on every square inch. The total pressure on the surface of a full-sized man would thus amount to about 17 tons.

That the body is not crushed is due to the fact that the outward pressure from within is equal to the inward pressure from without. This may be illustrated by use of a glass bottle with fragile walls. As long as the air-pressure is the same inside and outside, the bottle is not broken, but when air is pumped out, the glass will be shattered.

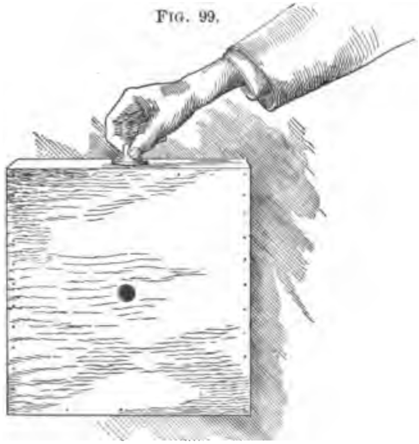
Experiment 26.

Cut out a circular piece of heavy leather about three inches in diameter. Fasten a stout string to the center of one side by stitching into the leather but not through it.

Oil the leather and work it until it is soft and pliable. Press it down upon the smooth surface of a block, stone, piece of iron, or other object. If it does not fit closely, use a little vaseline. Pull on the string. The central part of the leather disk is raised, producing an air-vacuum beneath it.

The air pressure being partly removed from the top of the object, the excess of pressure upward on the lower side may be sufficient to raise the object against the force of gravity.

FIG. 99.



Part of the air-pressure removed from top of box by use of a rubber cup. The box is lifted by the excess of air-pressure on the bottom.

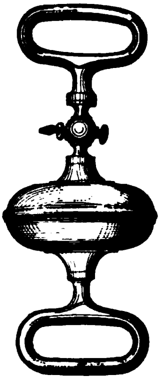
Experiment 27.

The Magdeburg hemispheres are two metallic hemispheres with ground edges and provided with handles and a stopcock.

When they are pressed together they should fit air-tight. A little vaseline on the edges will assist in making a tight joint.

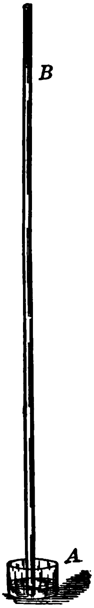
Pump out as much air as possible. Grasp the handles and attempt to pull the hemispheres apart. Measure the internal diameter and calculate the area of the section through the juncture of the hemispheres. The area in square centimeters multiplied 1033.3 gives the total pressure in grams when the barometric height is 76 cm. If the barometric height is less than 76 cm., the pressure will be proportionately less. This calculation gives the force necessary to pull the hemispheres apart when all the air is pumped out. In case only half the air is removed, then only half the force need be exerted.

FIG. 100.



Magdeburg hemispheres.

FIG. 101.



Barometer.

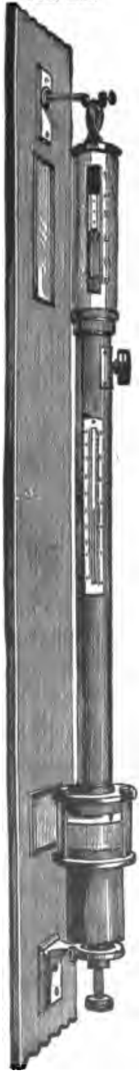
154. Barometer.

The barometer is an instrument for measuring the pressure of the atmosphere. The *mercurial* and the *aneroid* barometers are the two kinds in common use.

The *mercurial barometer* consists of a column of mercury balanced against the pressure of the air. A glass tube about 36 inches long is filled with mercury, one end of the tube being closed. The tube is then inverted, and placed so that the open end is submerged in mercury.

Since mercury is 13.6 times more dense than water, and water is 773 times as dense as air, a short column of mercury will press down on a square centimeter with a force as great as the air-pressure on the same area.

FIG. 102.



Fortin's mercurial barometer.

When the tube, shown in Fig. 101, was inverted, the mercury fell to some point, *B*, the length of the column then being *AB*, about 29 inches, or 73 cm.

The pressure of the air upon the surface of the mercury in the vessel is just balanced by the downward pressure of the column of mercury in the tube. As long as the air-pressure is constant, the height of the column of mercury remains unchanged. Any increase in the pressure of the air will cause more mercury to flow into the tube, and any decrease in pressure will allow some mercury to flow out of the tube into the vessel below.

In this way the barometer is used to determine the air-pressure of any place.

The space above the mercury in the tube is called a Torricellian vacuum. (See cyclopedia.)

(Minute directions for making a barometer may be found in the "First Book of Physics.")

The form of barometer shown in Fig. 102 is called Fortin's barometer. It is the same in principle as that described above, but it is constructed in a compact and convenient form.

At the bottom of this instrument is a mercury cistern the bottom of which is made of flexible leather. The leather rests on a thumb-screw. By turning this screw the mercury may be raised or lowered until it just touches the pointer which extends from the top of the cistern. This is the zero level to which the surface in the cistern must be set before reading the height at the top of the barometer.

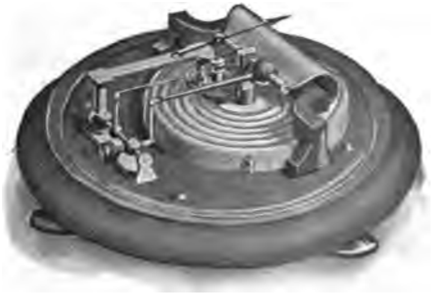
By turning the thumb-screw inward a sufficient distance, the cistern and tube may be completely filled and the barometer is then portable.

155. The Aneroid Barometer.

The aneroid barometer is so called because no liquid is used in its construction.

The essential part of it is a cylindrical metal box having a flexible top. The air is partly removed and the box is then sealed. The top is thus under a constant strain. Any increase in the air-pressure will push the flexible top in a little farther, and any decrease of pressure will allow the top to spring out. This movement is communicated by proper levers and gearing to a hand which is thus made to turn in front of a dial.

Fig. 103.



The aneroid.

This barometer can be made very sensitive, the difference in pressure between the floor and the top of a table being perceptible. Its portability gives it a great advantage over the mercurial type.

156. Use of a Barometer.

A barometer indicates only the pressure of the atmosphere. When the pressure increases or diminishes, the barometer changes accordingly.

Weather conditions may be inferred from changes in the height of the barometer. When the barometer is low, we expect foul weather, because the storm centers will move toward the region of low pressure. When the barometer is high we expect fair weather, for the movement of the air will be from that point.

The Weather Bureau of the United States has about one hundred and sixty stations at various points throughout the country and, from these, reports are sent to Washington every morning and evening. This report includes not only the reading of the barometer at that station, but also the humidity of the air, the temperature, the direction and velocity of the wind, and the rainfall.

From this data, principally from the barometric reading, a reliable forecast of the weather can be made several days in advance.

A barometer on the Sahara desert would rise and fall in accordance with the changes in the pressure of the air, and might be used to indicate the approach of wind, but would never indicate the approach of rain or snow in that locality.

Another important use of the barometer is in determining the altitude of localities. As one ascends higher above sea-level, the air-pressure grows less because there is less air above to exert a downward pressure at that point.

It is found by experiment that for every 900 feet of ascent near the earth, the column of mercury will fall about one inch. In this manner the height of a mountain may be approximately measured.

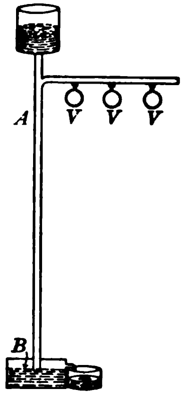
As temperature rises or altitude increases, the fall of one inch will indicate a change in altitude greater than 900 feet.

157. The Sprengel Pump.

The fact that there is a perfect air-vacuum at the top of the barometer tube, suggested the construction of a device known as the Sprengle air pump. The length of the tube from *A* to *B*, Fig. 104, is 76 cm. or more. The vessels *V*, from which air is to be extracted, are attached above the point *A*. The vessel at the top of the tube is kept full of mercury which slowly runs down through the tube. The air in *V* will constantly expand and push itself out into the tube where the stream of mercury will carry it down and out at the lower end. This may be continued until only one millionth of the original air remains in *V*.

The mercury will not run into *V* because the air pressure on the outside cannot support a column of mercury more than about 76 cm. high, and the pressure above only pushes more mercury straight down through the tube. There can be no lateral pressure of mercury on the sides of the tube where there is a Torricellian vacuum.

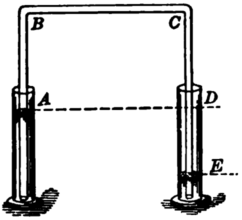
FIG. 104.



Sprengel pump.

This kind of pump has been extensively used in pumping air from incandescent lamps and other bulbs where a good vacuum is desired. It is slow in operation and is now largely replaced by improved mechanical pumps.

FIG. 105.



The siphon.

158. The Siphon.

The siphon is an instrument frequently used in conveying liquids from one vessel to another. Its action depends on the pressure of the air and the weight of the liquid.

In Fig. 105 the tube *ABCE* is a siphon. It is first filled with liquid, which will then flow from *A* through the tube to *E*. This flow will continue as long as there is a difference in the level of the liquids in the two vessels.

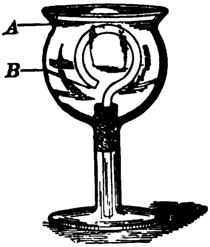
The explanation of the action of the siphon is as follows: The air-pressure at *A* and *E* is practically the same. Thus the liquid is forced up into the tube *AB* with the same force that it is forced up into *EC*. Hence there is equilibrium from these two opposing forces. The force of gravity, however, on the column of liquid *CE* is greater than that on the column *BA*. These forces are not, then, in equilibrium, and, as a free body will always move in the direction in which the greater force acts, the liquid will flow out at *E*.

The height of the top of the siphon, *BC*, above the liquid at *A* can never be greater than the height to which the air-pressure will raise the liquid. This height in case of mercury cannot be more than 76 cm. In case of water, about 1033.6 cm., or about 34 feet.

159. The Intermittent Siphon.

When the tube of the siphon is of such a size that the liquid will be carried from the vessel, Fig. 106, faster than it runs in, the action of the siphon will be intermittent. A constant stream of liquid may run into the cup, but the siphon will not act until the tube is filled. Then it will lower the level of the liquid from *A* to *B*. Action will then cease until the water again rises to the level *A*.

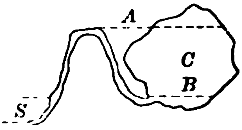
FIG. 106.



Intermittent siphon.

This siphon is interesting as an explanation of intermittent springs where water flows from the side of a hill at intervals of a half hour, hour, or some other regular interval. A formation in the earth which would produce such action may be such as shown in Fig. 107. *C* is a cavity into which water gradually seeps from the rock above. When the cavity is filled to the level *A*, water will begin to run from *S*. Since the siphon runs the water out faster than it runs in, the level of water will soon be lowered to *B*, when the siphon will cease to act until the cavity again is filled.

FIG. 107.



Intermittent spring.

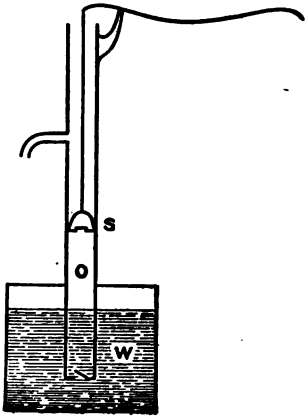
160. The Lifting Pump.

A lifting pump is a contrivance used in raising liquids by aid of air-pressure.

It consists essentially of a stock the lower end of which extends into the liquid, a sucker which can be moved up and down within the stock, and two valves, one at the bottom of the stock and the other in the sucker, both opening upward only.

The sucker closely fits the bore of the stock and when it is raised the air above it is lifted. The air in the space *O* will thus be given more room and so will not exert as great force downward upon the lower valve as the outside air-pressure exerts inward at that point. Thus some liquid will be pushed through the lower valve into the stock.

FIG. 108.



Lifting pump.

The purpose of priming a pump by pouring water in at the top is to make the sucker fit closely and prevent the passage of air down to *O* while the pump is being started.

While the sucker is rising, its valve is closed and the lower one open. When the sucker is pushed down, the lower valve is closed by the outward flow of the water itself, while the sucker-valve is pushed open by the compressed air or water below it.

After the pump is started, every upward stroke of the sucker lifts the water above and removes the downward pressure on the water in the stock below.

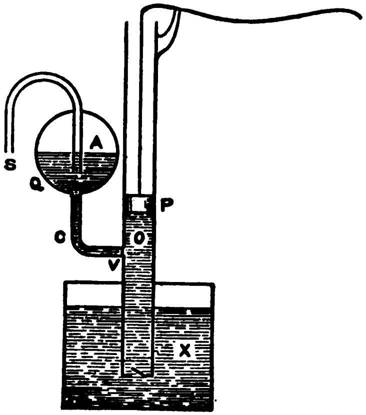
The outside air-pressure pushes the water through the lower valve into *O*,—the space between the two valves. The water above the sucker is lifted up to the spout.

Since the pressure of the air cannot support a column of water more than about thirty-four feet high, the valve in the sucker must never exceed that distance from the water. In practice, the sucker should not be more than fifteen or twenty feet from the water.

There must be two valves in this pump as in all pumps. Any extra valves placed at other points within the stock would be of no advantage.

The ordinary air pump does not differ in principle from the pump just described, but it is more accurately constructed.

FIG. 109.



The force pump.

161. The Force Pump.

In the force pump a solid plunger *P*, Fig. 109, takes the place of the sucker of the lifting pump. There are two valves, one at the bottom of the stock and the other at the entrance to a side opening, *V*.

When the plunger is raised, water enters the chamber *O*, just as in the lifting pump, but when the plunger is pushed down, the valve at *X* will be closed, *V* will be pushed open, and the water will be forced out through the pipe *C*.

Water from such a pump will spurt out at the spout with force each time the plunger is pushed down. By attaching a condenser, *Q*, advantage may be taken of the compressibility and elasticity of air to make the water issue from the spout in a steady stream. The water is forced by spurts into the chamber *Q*; the air, *A*, is compressed and exerts a nearly steady pressure upon the water, forcing it out at *S*.

Both the lifting and the force pump will operate independently of any air pressure provided the sucker or plunger, as well as the lower valve, are beneath the surface of the liquid which is to be pumped.

162. Work of Pumps.

Pumps are machines and are subject to the general law of machines. One pump may differ in construction from another, but all require the same expenditure of energy for the same amount of work.

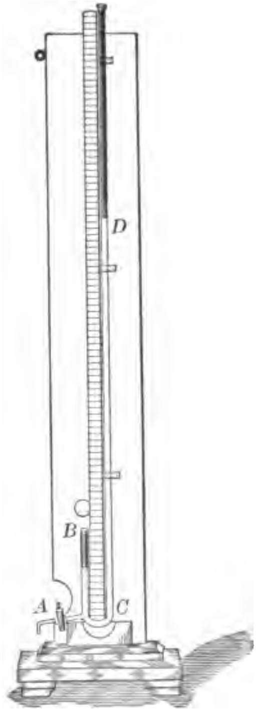
One pump may have a long handle and may be operated by a small force, but this small force must be moved through a proportionately greater distance to raise the same amount of water as the pump with a short handle. It requires about 6240 foot-pounds of work to raise a cubic foot of water from a well 100 feet deep, and the amount of energy needed for the work is the same no matter what agency is employed.

163. Boyle's Law.

An important law of gases know as Boyle's or Mariotte's law may be stated as follows: *The product of the pressure and volume of a given mass of gas is constant if the temperature is constant.*

To illustrate this law suppose we have 60 c.c. of gas, air say, under a pressure of 50 cm. of mercury. The product of the pressure and the volume would then be 3000. If then the pressure is raised to 100 cm., the volume will be only 30 c.c., but the product will be 3000. If the pressure becomes 200 cm., the volume will be 15 c.c. but the product will still be 3000. It is assumed that the temperature remains unchanged during these changes in pressure.

FIG. 110.



Boyle's law apparatus.

This law may be stated in the concise formula

$$PV = P'V'$$

in which *P* and *V* represent a given pressure and volume and *P'* and *V'* represent corresponding quantities after the pressure is changed.

Suppose, for example, it is known that the volume of a body of gas at 76 cm. pressure is 100 c.c. and it is desired to know what its volume would be at a pressure of 74 cm. It is seen that three of the quantities in the formula are given, and so the fourth can easily be found; thus

$$76 \times 100 = 74 \times V'$$
$$\therefore V' = 102.7 \text{ c.c.}$$

Boyle's law may be demonstrated by use of a U-shaped tube such as is shown in Fig. 110. The upper end of the short arm is closed but the long arm is open. The mercury is first adjusted so that it stands at the zero mark in both arms. A column of air is thus enclosed in *AB* and its length can be taken as a measure of its volume. As long as the mercury is at the same height in both arms, the air-pressure in each arm must be equal. If, now, mercury be poured into the long arm, the pressure on that side will be the air-pressure plus a column of mercury equal to the height in the long arm above that in the short arm.

The mercury will also rise a short distance in *AB*, compressing the air there into smaller volume. By keeping a record of the volume of this air and the various pressures to which it is subjected, the constancy of *PV* may be shown.

Boyle's law is not rigidly true, the product of pressure and volume being less than that required by the law in case of many gases, particularly at high pressures.

Within moderate limits, however, the law is extremely useful in many calculations.

164. Pressure, Volume, and Elastic Force.

The pressure, volume, and elastic force of a gas are so related that any change in one involves a change in one or both of the others.

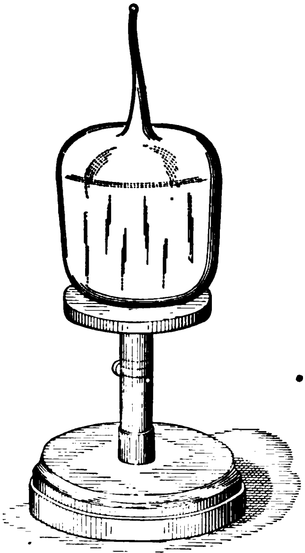
Increase of pressure causes a decrease of volume and an increase of elastic force.

Elastic force decreases as the volume increases.

Experiment 28.

Fill a rubber bag or small foot-ball partly full of air. Close it tightly and place it under the receiver of an air pump. As the air is gradually pumped from the receiver, the pressure upon the bag will be removed and the air within will increase in volume, distending the walls of the bag. When air is again admitted into the receiver, the air in the bag will be compressed to its former volume; or, illustrating the same principle, place a cube of thin glass, called a "bursting cube," under the receiver. The cube is sealed, and, when the air in the receiver is

FIG. 111.



Bursting cube.

removed, the unbalanced outward pressure of the air within the cube is great enough to burst the cube. Instead of removing the pressure from the outside of the cube, the point may be broken and the air removed from the inside. In this case the cube will be broken by the unbalanced outside pressure.

165. Diffusion of Gases.

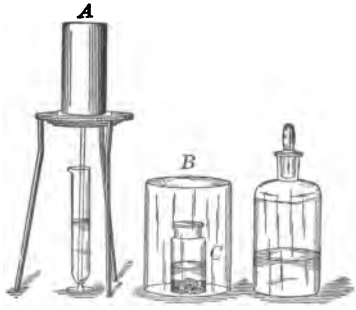
Diffusion of gases is a process by which the molecules of one gas mingle with those of another until they are equally distributed throughout the whole space formerly occupied by the two gases separately. A small quantity of ammonia gas, for example, may soon be detected throughout the air in a room.

The lighter a gas is, the more rapidly it will diffuse. The rate of diffusion varies inversely as the square root of the weight. Oxygen is sixteen times as heavy as hydrogen, therefore, hydrogen will diffuse four times as fast as oxygen. This law is only approximately correct.

Experiment 29.

The rapid mingling of hydrogen with air may be demonstrated by use of the apparatus shown in Fig. 112. *A* is a small porous cup such as is often used to separate the liquids of a two-fluid battery. Its open end has been closed with plaster of Paris through which a glass tube passes.

FIG. 112.



Apparatus for illustration of diffusion.

The cup thus prepared is inverted and placed so that the end of the tube is about 1 cm. beneath the surface of the water.

Now place some scraps of zinc in the small bottle, *C*, and cover them with water. Add 4 or 5 c.c. of hydrochloric acid. Hydrogen will be rapidly evolved. Place the jar *B* over the bottle for a minute or two and then lift it to a position over the porous cup. Bubbles will escape from the lower end of the glass tube, showing that the hydrogen has passed more rapidly into the cup than the air has passed in the opposite direction.

When the jar is removed, water will rise in the glass tube, showing that the hydrogen now moves out through the walls of the cup faster than the air moves in.

After a short time the water will sink to its former level, showing that the diffusion is complete.

Problems.

1. Compute the volume of 1 kg. of air under standard conditions of temperature and pressure. *Ans.* 773.4 l.

2. What is the total air-pressure at sea-level upon a man the surface of whose body measures 16 square feet. *Ans.* 17 tons, nearly.

3. If at the plane where the Magdeburg hemispheres separate, the section is 10 cm. in diameter, what force will be needed to pull the hemispheres apart when half the air is pumped out? *Ans.* 40,577.69 g.

4. What is the force per square centimeter when the pressure is 5 atmospheres? *Ans.* 5,064,640 dynes.

5. What will be the buoyant force of the air on a balloon 50 feet in diameter? If the balloon is filled with hydrogen, and density of air be taken as 14.5 times as great as hydrogen, what weight, including the balloon and its trappings, can be raised when the barometer shows standard pressure? *Ans.* 5236 lbs. and 4874.9 lbs.

6. What is the air pressure per square centimeter when the height of the barometric column is 780 mm.? *Ans.* 1060.8 g.

7. If the volume of a body of gas under a pressure of 760 mm. is 2850 c.c., what will be its volume when the pressure is reduced to 720 mm.? *Ans.* 3008.33 c.c.

8. If, when the barometric pressure is 760 mm. a barometer of proper length be lowered, in a diving bell, to a depth of 560 cm. below the surface of fresh water, what will be the height of the column of mercury? How much of the space in the bell will be filled with water? *Ans.* (1) 117.176 cm. (2) .352.

9. If, when the barometer stands at 74 cm., 8560 c.c. of air be pumped into a vessel whose capacity is 107 c.c., what will be the elastic force per square centimeter on the interior of the vessel? *Ans.* 80,512 g.

10. How high would the atmosphere need to be to produce a pressure at sea-level of 14.7 lbs. per square inch, assuming it all to have the same density as that under standard conditions? *Ans.* 26,460 feet, or 5 miles nearly.

CHAPTER XI.

HEAT.

166. Nature of Heat.

Heat is molecular motion. Heat is, then, not a substance but a condition of a substance. The molecules of which all matter is composed are at all times in motion. When the motion is rapid, we say that the body is hot, or contains heat. When the motion is slow, the body is said to be cold.

We heat a body only by making its molecules move more rapidly, and cool it by making them move more slowly.

This conception of the nature of heat should be constantly kept in mind while attempting to explain the phenomena of heat.

167. Sources of Heat.

Our chief sources of heat are the *sun*, *chemical action*, *electricity*, *friction*, and *percussion*. Heat, as such, may not come from or exist in these sources, but they are the agents which may cause increased molecular motion in bodies of matter.

168. The Sun as a Source of Heat.

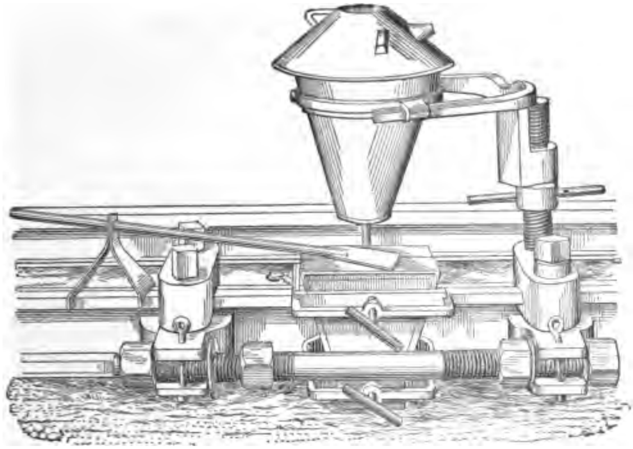
The sun is the source of nearly all the heat on the earth. Its rays warm the air, land, and water, and indirectly it is the source of all the heat obtained from fuel. The sun is a large sphere nearly 860,000 miles in diameter. It radiates heat in all directions. The earth, at a distance of about 93,000,000 miles, intercepts a few of these radiations and is warmed. The other planets are warmed in a similar manner. The sun is constantly shrinking, but it is so vast in size and contains so much heat that many thousands of years will elapse before there is any perceptible change in its size or in the quantity of heat which the earth receives.

169. Heat from Chemical Action.

Nearly all the heat used in warming the air in buildings, in heating the water in boilers, in cooking, in fact in all the arts, is obtained from chemical action.

Coal, wood, gas, and oil are very common fuels. They are fuels because they possess potential energy. Their energy consists in the fact that they are composed chiefly of molecules of carbon and hydrogen which have a strong affinity for oxygen. Under proper conditions the oxygen and the carbon or hydrogen will be drawn violently together. The result will be a rapid agitation of the molecules, and this is what we call heat.

Fig. 113.



Use of thermit in welding the end of steel rails.

The sun, ages ago, separated oxygen from the carbon in the growth of green plants, so the heat which we now get from coal may also be considered as having its origin in the sun.

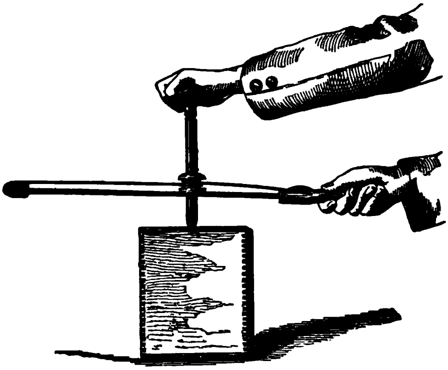
Heat is also obtained from other kinds of chemical action. If sulphuric acid is poured in a fine stream into water, the mixture will become very warm.

"Thermit" is a mixture of powdered aluminum and iron oxide. When by use of a proper fuse these two substances are made to unite, an intense heat results and the molten metal which is thus obtained will readily melt its way through heavy plates of iron, or fuse and weld the ends of heavy iron rails.

170. Heat from Friction.

Considerable heat is produced by the friction of one body in motion against another. A metal button rubbed on the sleeve becomes very warm. A car-brake often sends off a shower of sparks as a result of its friction against the wheel. When a pointed stick is rotated with its point pressed against a dry board, volumes of smoke will rise and a fire may be started.

FIG. 114.

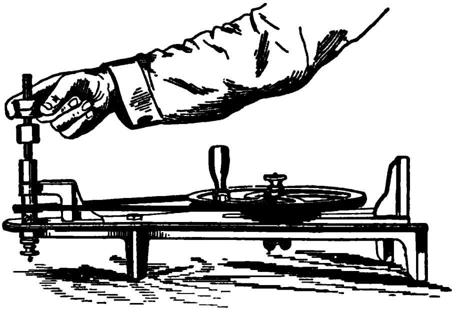


Starting fire by friction.

Experiment 30.

Mount upon a rotator a brass tube as shown in Fig. 115. Pour into the tube about 3 c.c. of ether or carbon disulphide and cork it fairly tight. A split cork fits loosely over the tube.

FIG. 115.



Heat by friction.

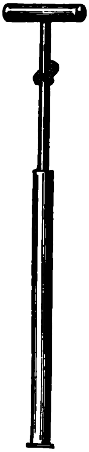
When the rotator is operated, the halves of the cork may be pressed as firmly as desired against the tube, and the heat resulting from the friction will vaporize some of the liquid, forcing out the cork.

Friction is seldom employed as a means of producing heat. In most machines it is desirable that friction and the resulting heat be avoided.

170a. Percussion.

When the motion of a body is suddenly arrested, its motion is converted into molecular motion, or heat. The head of a nail is heated by the stroke of a hammer. A lead bullet may be melted when it is suddenly stopped in its flight. A flash of light is seen where a cannon-ball strikes a metal target. Numerous examples of heat from percussion, or striking, may be given.

FIG. 116.



Fire syringe.

The heat from steady pressure may also be classed under this head. An illustration may be found in the "fire syringe." A quantity of air is compressed by pushing down the piston. The air is heated sufficiently to ignite a piece of punk placed in the lower end of the piston.

171. Heat from the Electric Current.

The energy in the electric current is often converted into heat. The heat, as will be explained later, results from the attempt to force more electricity through a conductor than it is able to carry.

Electric cook-stoves, soldering-irons, smoothing-irons, and heaters are in common use.

The intense heat of the arc-light is used on a large scale in the electric furnace. Such a furnace is employed in the manufacture of aluminum, calcium carbide, carborundum and other products.

172. Temperature.

Temperature is the state of a body in reference to its molecular activity. When the motion of the molecules of one body is more rapid than that of another, the former is said to have a higher temperature. Heat is always transmitted from bodies of higher to bodies of lower temperature.

173. Quantity of Heat.

The total amount of energy due to molecular activity within a body, is a measure of the quantity of heat which it contains. The *temperature* and the *quantity of heat* should be clearly distinguished. The temperature of a cubic centimeter of water may be the same as that of a liter, but the quantity of heat in the liter would be one thousand times greater than that in the cubic centimeter, because there would be one thousand times as many molecules in motion. A pint of boiling water does not contain any more heat than a gallon of ordinary drinking water.

174. Measurement of Temperature.—Thermometers.

Temperature is measured by means of a thermometer. The common form of thermometer consists of a glass tube containing mercury. A bulb is blown on one end of the tube and filled with mercury. When both glass and mercury are heated the mercury expands more than the glass does, and will find the extra space needed by rising in the fine capillary bore of the stem. The bore is so fine that a very slight change in the volume of mercury will cause a perceptible change in the length of the thread of mercury in the stem. The cylindrical stem acts as a magnifying glass and makes the thread of mercury look much larger than it is.

Mercury is the best liquid for use in a thermometer for several reasons:

(1) Mercury remains a liquid through a wide range of temperature—from about 40° C. below the freezing point of water to 350° C. above.

(2) The rate of expansion of mercury is nearly constant within the limits of such a thermometer.

(3) Mercury conducts heat very readily, and therefore it can be rapidly heated or cooled.

(4) Mercury does not wet the glass in which it is contained.

175. Graduation of Thermometers.

There are two points on a thermometer which can be readily determined. One is the height of the mercury when the bulb is packed in melting ice, and the other, when the whole thermometer is immersed in the vapor of boiling water.

While ice is melting or water is boiling, the temperature is constant. This gives opportunity to mark these two points.

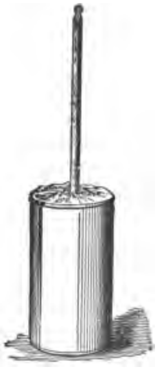
Experiment 31.

Crush about a half liter of ice and pack it, in any suitable vessel, about the bulb of a thermometer, so that the top of the thread of mercury is just visible above the ice. Try this experiment with both a Centigrade and a Fahrenheit thermometer. The top of the mercury should be at the freezing point marked on the scales.

Experiment 32.

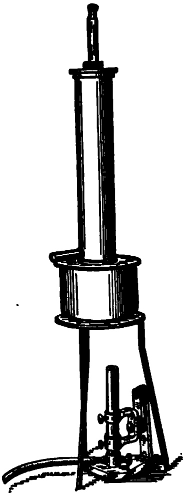
Boil some water in a vessel such as is shown in Fig. 118. The brass tube is double, one tube being concentric within the other. The steam rises about the thermometer in the inner tube and descends through the space between the two tubes to an outlet at the lower end. The top of the tube is closed with a cork through the center of which a thermometer is passed. The bulb of the thermometer should not reach the water, for water containing impurities will have a different temperature from the vapor which rises from it. Raise or lower the thermometer until the top of the mercury can just be seen above the cork. When the mercury has ceased to rise, compare its height with the boiling point marked on the stem. These will not be the same unless the atmospheric pressure at the time is 76 cm. The effect of pressure on the boiling point will be explained in a later paragraph.

Fig. 117.



Zero point.

Fig. 118.



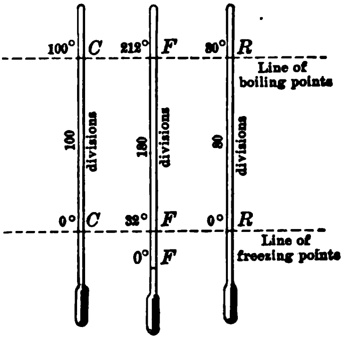
The boiling point.

176. Three Kinds of Graduations.

There are three kinds of thermometers in common use—the *Centigrade*, *Fahrenheit*, and *Reaumur*. The difference between them consists in the number of divisions between the freezing and boiling points and in the numbers applied to these divisions.

The Centigrade thermometer is the best and most convenient of the three. It is used for all scientific purposes, and in some parts of Europe for all purposes. In it the freezing point is marked 0° and the boiling point, 100°. Thus the intervening space is divided into 100 equal parts.

FIG. 119.



Comparison of thermometers.

The Fahrenheit thermometer is in common use among English speaking people for domestic purposes. This thermometer possesses no advantage over the Centigrade except that it has long been in use. The space between freezing and boiling points is divided into 180 equal parts and the zero is 32 of these divisions below freezing. The boiling point is then $32 + 180 = 212°$.

The Reaumur thermometer is used for domestic purposes in Continental Europe. It has nothing to recommend it. The freezing point is marked 0° and the boiling point, 80°.

177. Comparison of the Three Scales.

It is seen, in the description given above, that the number of divisions between freezing and boiling points is, in the order given, 100, 180, and 80. Hence each division on the Centigrade scale is $\frac{9}{5}$ as large as one on the Fahrenheit and $\frac{4}{5}$ as large as one on the Reaumur. There would then be $\frac{5}{9}$ as many divisions on the Centigrade as on a similar space on the Fahrenheit scale, and $\frac{5}{4}$ as many as on the Reaumur.

To change from the reading on any one of these scales to that on any other,

$$\begin{aligned}
C. &= \tfrac{5}{9}\,(F. - 32).\\
C. &= \tfrac{5}{4}\,R.\\
F. &= \tfrac{9}{5}\,C. + 32.\\
F. &= \tfrac{9}{4}\,R. + 32.\\
R. &= \tfrac{4}{5}\,C.\\
R. &= \tfrac{4}{9}\,(F. - 32).
\end{aligned}$$

By use of these equations the corresponding value of any reading may be readily made, but it is better to study the diagram in § 176 and notice that whenever a change is to be made from C. or R. to F., the proper fractional parts are first taken and the 32 then added, while in changing from F. to either of the other two, the 32 is first subtracted. The fractions apply only to the number of divisions between freezing and boiling.

178. Unit of Quantity of Heat.

The unit usually employed in measuring the quantity of heat is called the *calorie*. It is defined as the quantity of heat needed to raise the temperature of 1 g. of pure water 1° C. It is often called the *gram-calorie*.

If water, then, is the substance under consideration, it is easy to calculate the number of calories of heat needed to raise any given mass of it through a certain number of degrees, or the number of calories of heat given out by the water when it is cooled.

Problems.

1. How many degrees on the Centigrade scale corresponds to 78° on the Fahrenheit? *Ans.* $43\frac{1}{3}$.

2. When the Fahrenheit thermometer indicates a temperature of 98.5°, what would be the reading on the Centigrade scale? *Ans.* 36.94°.

3. From — 10 F. to 45 F. is what range C.? *Ans.* 30.55°.

4. — 40° C. is what temperature F.? *Ans.* — 40°.

5. 40° R. is what temperature F.? *Ans.* 122°.

6. What is the temperature when the sum of the readings of a Centigrade and a Fahrenheit thermometer is 150. *Ans.* $42\frac{1}{7}$° C.

7. If one liter of water is heated until its temperature rises 20° C., how much heat does it receive? *Ans.* 20,000 cal.

8. If 50 g. of water is cooled 77° F., how much heat is taken from it? *Ans.* 2138.55 cal.

9. When 40 g. of water, at 30 C. loses 250 cal. of heat, what will be its temperature? *Ans.* 23.75° C.

10. How much water will be needed to yield 6250 cal. of heat by a decrease of 12° C. in temperature? *Ans.* 520.833 g.

179. Effect of Heat on the State of a Body.

Most substances may be made to pass from a solid to a liquid and then to a gaseous state by the application of the requisite amount of heat. Some substances, such as wood, appear to pass directly from a solid to a gaseous state.

FIG. 120.

Principle of the electric furnace.

Substances such as lead, cast iron, zinc, and others, remain a solid until they are heated to a certain temperature called the melting point, and then they rapidly change to the liquid state.

Other substances, such as glass, wax, and others, gradually become soft and viscous, becoming more and more like a liquid as the temperature increases.

The temperature of the arc-light is about 3500° C. The lowest temperature which has been produced is about 260° C. below 0° C.

With this range of temperature many solids have been converted to liquids and gases, and many gases, such as hydrogen, have been changed to solids.

By the intense heat of the electric arc, as used in the electric furnace or some modification of it, lime and coke are made to unite chemically, producing *calcium carbide.* By use of this high temperature, *aluminum* is extracted from clay. By use of a similar temperature, sand and coke are united into a compound called *carborundum* which, next to the diamond, is the hardest of substances and is extensively used as an abrasive.

FIG. 121.

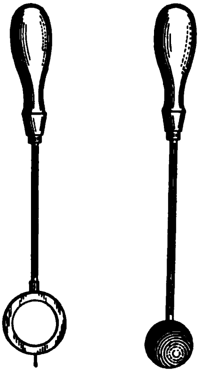


Illustration of expansion.

180. Expansion Caused by Heat.

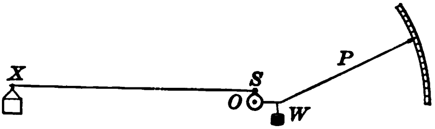
If heat is molecular motion, then any increase in the temperature of a body would require an increase in the rapidity of motion of the molecules. The molecules by their more frequent and violent collisions would be separated a little farther from one another and, as we would expect, the body expands. Heat, alone, always causes bodies to expand.

Expansion as a result of heat may be illustrated in many ways. If the brass ball (Fig. 121) which just passes through the ring, is heated, it will be much larger than the opening in the ring. If the ring also is heated, the ball will then easily pass through. The brass of the ring also expands, increasing in thickness, and to that extent making the opening smaller, but the circumference is so much greater than the thickness that the total effect is to increase the diameter of the ring.

Experiment 33.

Stretch a copper wire, about 50 cm. in length, from a rigid support, *X*, Fig. 122, to *S*, the end of the short arm of a lever whose fulcrum is at the center of *O*. *P* is a long, stiff pointer. Suspend a weight at *W* to keep the wire taut. Heat the wire by moving a flame back and forth beneath it. The end of the pointer moves over a scale graduated in centimeters or inches, and the amount of expansion of the wire can be calculated when the lengths of the arms of the lever are known.

FIG. 122



Expansion of a wire.

Solids, liquids, and gases all expand when heat is applied to them.

The expansion occurs in all directions, though only one direction may be considered, as in the experiment just given. It is then called *linear expansion.*

The increase in two directions, that is, increase in the area of a surface, may be considered, and it is then called *superficial expansion.*

When the increase in all three directions is considered, it is called *cubical expansion.*

181. Coefficient of Expansion.

The amount of expansion for different substances is not the same for the same change in temperature. It would plainly be an advantage if we knew how much each substance would expand when heated one degree.

Careful experiments have been made to find for each substance a factor called the *coefficient of expansion,* Since expansion is considered in reference to one, two, or three dimensions, there will be three kinds of coefficients.

The *coefficient of linear expansion* is the fraction expressing the part of its length that a body expands when its temperature is raised from 0° C. to 1° C. Thus, the linear coefficient for iron is .0000122. When an iron rod is heated 1° C. its length is increased .0000122 of itself. If heated 10° C. the increase in length would be ten times as much.

The length of a body after its temperature has been raised would be its length before, plus the increase from expansion.

Expressed in formula, this would be

$$L_t = L_0 + L_0 lt, \text{ or}$$
$$L_t = L_0 (1 + lt),$$

where L_t represents the length at any temperature; L_0 the length before heat is applied; l, the coefficient of linear expansion; and t, the temperature.

From this it can be seen that when the length and coefficient of any substance is known, it is easy to calculate its length when its temperature is increased any given number of degrees.

In most substances the coefficient is nearly the same for each degree.

The *coefficient of superficial expansion* is the fraction expressing the part of its area that a body expands when its temperature is raised from 0° C. to 1° C. The formula for calculation of area after expansion is

$$A_t = A_0 + A_0 at, \text{ or}$$
$$A_t = A_0 (1 + at)$$

where a is the coefficient of superficial expansion, the A_t representing the area after the increase of temperature, and A_0 before.

The value of a is equal to $2l$, and so the formula for area may be written

$$A_t = A_0 (1 + 2lt).$$

The *coefficient of cubical expansion* is the fraction expressing the part of its volume that a body expands when its temperature is raised from 0° C. to 1° C. The formula for calculation of volume after expansion is

$$V_t = V_0 + V_0vt \quad \text{or}$$
$$V_t = V_0(1 + vt)$$

where *v* is the coefficient of cubical expansion.

The value of *v* is equal to 3*l*, and so the formula may be written

$$V_t = V_0(1 + 3lt).$$

The coefficients for several substances are given in Appendix VI.

182. Some Advantages and Some Disadvantages of Expansion.

Plates of iron are fastened together with red-hot rivets. When the rivets cool they contract and bind the plates together with great force.

Iron tires are first heated and then put onto the carriage wheel. When the iron cools, the tire contracts and binds the wheel.

In the construction of long strands of wire fence, provision is made at one end for taking up the wire in summer time, and letting it out in winter time.

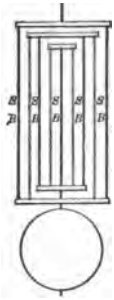
A short space is left between the rails on a railroad, to permit expansion and contraction without injury to the road.

One end, at least, of long bridges, is supported on rollers and allowed freedom of motion.

The unequal expansion of some substances is utilized in various ways.

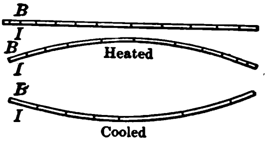
The gridiron pendulum consists of a number of parallel rods of brass and steel arranged so that while the expansion of the steel rods lowers the bob, the expansion of the brass will raise it. The arrangement of the rods is illustrated in Fig. 123. The steel rod from which the bob hangs passes freely through holes in the two lower cross-pieces. The ratio of the combined length of the steel rods to the combined length of the brass ones is inversely as the coefficients of linear expansion of these metals. Thus, the pendulum is kept at a constant length however much the temperature may vary.

FIG. 123.



Gridiron pendulum.

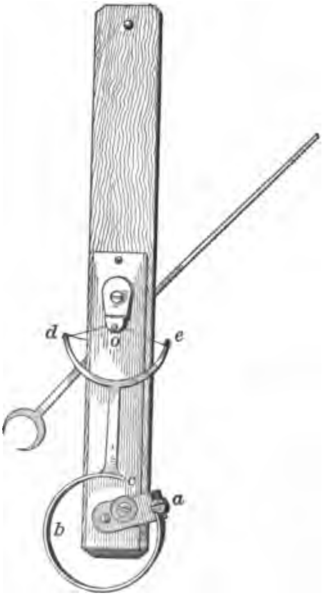
FIG. 124.



Bars of brass and iron riveted together and subjected to changes of temperature.

If strips of brass and iron be riveted together, and heated, they will bend into an arc of a circle with the brass on the outside. This is because brass expands more than iron does for the same change in temperature, and the outer edge of a ring is longer than the inner. When the bar is cooled in ice, it will bend, for a similar reason, so that the brass is on the inside of the arc.

FIG. 125.



Metal thermometer.

This principle is utilized in the construction of metal thermometers. *abc*, Fig. 125, is the compound bar of brass and steel which is rigidly fastened at *a*. A long hand is attached to an axis *o*. A thread is wrapped once about the axis and stretched between *d* and *e*. The compound bar curves more or less as the temperature changes, thus pulling the thread one way or another and moving the hand. The hand moves in front of a dial which is graduated in degrees.

The chronometer balance wheel of a watch is so constructed that it will automatically correct errors in time which would result from changes in temperature. Each student should examine such a balance wheel and explain how the principles just given are applicable.

183. Apparent Exceptions to the Law of Expansion.

As already stated, there can be no exception to the law that heat, alone, will always cause a body to expand. The theory of heat, if true, makes the law universal. Other changes, however, may occur during the heating or cooling of a body, and such changes may also affect the volume.

The most notable apparent exception is the change in the volume of water when its temperature is reduced to near the freezing point. Water, when cooled, will decrease in volume until its temperature is 4° C. It is then at its point of maximum density. If cooled still more, its volume will increase until it is crystallized and converted to a solid—ice. If the temperature is reduced below 0° C., the ice will decrease in volume.

The cause of the expansion is probably due, not to the cooling, but to the molecular rearrangement necessary to crystallization.

Cast iron and bismuth also expand on solidification.

The density of ice at 0° C. is .91674. The increase in volume of 1 g. when it changes from water at 0° C. to ice at 0° C. is .0907 c.c.

The fact that water expands on solidification is a great advantage in the economy of nature. When water is colder than 4° C. it will float on the surface of lakes and ponds. This colder water will be the first to freeze, and the surface layer of ice will not only protect the aquatic life beneath, but may readily be melted in the following spring.

The force of expansion when water freezes is enormous.

Experiment 34.

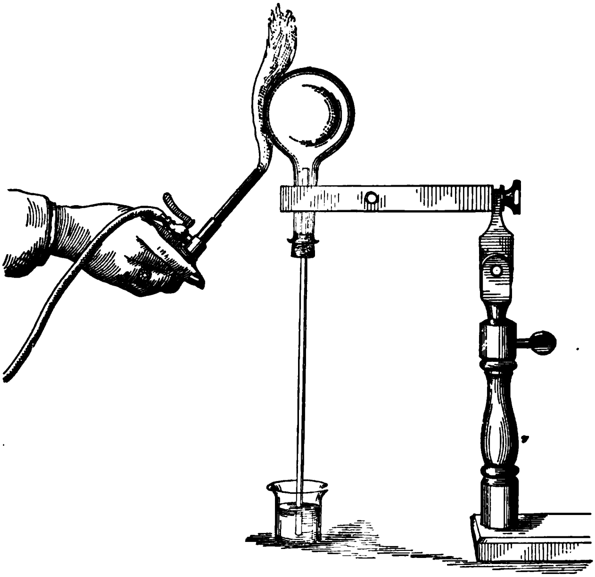
Fill with water a strong closed vessel. The vessel may be a strong bottle or one made of thick cast iron. Expose it to the cold until the water freezes. The vessel will be burst to make room for the expanding ice. This principle is utilized in nature in the disintegration of rock and the formation of soil.

The bursting of water pipes and other water containers may be counted among the disadvantages resulting from the fact that water expands on freezing.

184. Expansion of Gases.—Law of Charles.

When a flask of air is heated in the manner shown in Fig. 126, the volume of air which bubbles from the lower

FIG. 126.



Expansion of air.

end of the tube shows that the gas expands promptly and with a large coefficient when it is heated.

A law, known as the law of Charles or Gay-Lussac, states that *all gases have the same coefficient of thermal expansion, or, stated in another way, a given volume of any gas under constant pressure increases by a constant fraction of its volume at* 0° *C. when its temperature is increased* 1° *C.*

The constant fraction for all true gases is .0036625, or $\frac{1}{273}$.

The volume of a gas at any temperature may be compared with its volume at 0° C. by use of the regular formula for cubical expansion.

$$V_t = V_0 (1 + vt) \text{ or, for gases,}$$
$$V_t = V_0 (1 + \tfrac{1}{273} t)$$

If, for example, 900 c.c. of gas at 0° C. is heated to a temperature of 80° C., its volume will then be

$$V_t = 900 (1 + \tfrac{80}{273}) = 1163.74 \text{ c.c.}$$

This law is true only while the pressure remains constant. If the pressure also changes, then Boyle's law (§ 163) must enter into the computation at the same time. According to Boyle's law,

$$PV = P'V',$$

if the temperature remains constant. That is,

$$P : P' = V' : V.$$

Suppose, in the example above, that the pressure also changed from, say, 76 cm. to 70 cm., then,

$$76 : 70 = V' : 1163.74.$$
$$\therefore V' = 1263.45 \text{ c.c.}$$

185. Absolute Temperature.

If the temperature of a body of gas under constant pressure be reduced 1° C. below 0° C., the volume will be reduced $\frac{1}{273}$. If the temperature is reduced to — 10° C., the volume will be reduced $\frac{10}{273}$. If the temperature is — 273° C., the volume will be reduced $\frac{273}{273}$.

By substituting — 273° C. in the formula for the law of Charles,

$$V_t = V_0 \left(1 + \frac{-273}{273}\right).$$
$$\therefore V_t = 0.$$

Hence at — 273° C. both the volume and the pressure of a gas becomes zero, and since we cannot conceive of any temperature lower than that, this point is called the *absolute zero* of temperature.

The temperature as reckoned from this point is called the *absolute temperature.*

On the Fahrenheit scale the absolute zero is — 460° F.

The absolute temperature may always be found by adding 273 to the ordinary readings on the Centigrade scale, and 460 to the readings on the Fahrenheit scale.

$$\text{Since } V_t = V_0 \left(1 + \frac{1}{273} t\right)$$
$$V_t = V_0 + \frac{V_0}{273} t$$
$$V_t = \frac{V_0 \,(273 + t)}{273}, \text{ by a slight change of form.}$$

The V_0 and the 273 in the last formula are constant quantities, hence V_t will vary as $(273 + t)$ varies. But $273 + t$ is the absolute temperature, T. Hence the volume of a body of gas at constant temperature varies directly as the absolute temperature varies.

Suppose 900 c.c. of a gas is heated till its temperature rises from 0° C to 80° C. Its volume may then be found by the proportion

$$V_t : V_0 = T' : T$$
$$\text{Substituting values, } V_t : 900 = 273 + 80 : 273.$$
$$\therefore V_t = 1163.74 \text{ c.c.}$$

When a change in both the temperature and the pressure are to be considered, a compound proportion may be formed in which the volumes will vary directly as the absolute temperatures and inversely as the pressures.

Since the mass of any volume of gas varies directly as the pressure and inversely as the absolute temperature, the change in the mass of a body of gas can be calculated by use of a compound proportion in which the ratio of the masses is put equal to the direct ratio of the pressures and the inverse ratio of the absolute temperatures.

$$\text{Thus,}\quad M' : M'' = \left\{ \begin{array}{l} P' : P'' \\ T'' : T' \end{array} \right.$$

The *standard conditions* for a gas are 0° C. and 76 cm. pressure. Under such conditions a cubic centimeter of air weighs .001293 g.

Problems.

1. A copper wire is 475 feet long when the temperature is 0° C., what will be its length when the temperature is 28° C. ? *Ans.* 475.23 feet.

2. How much will 200 m. of iron wire shrink in length when its temperature is reduced 50° C.? *Ans.* 12 cm.

3. If a metal rod is 19,988 cm. long at 0° C., and 20,000 cm. long at 50° C., what is its mean coefficient of linear expansion? *Ans.* .000012.

4. A steel rod 1 m. long at 10° C., will be how much longer at a temperature of 40° C.? *Ans.* .33 mm.

5. A tin plate is 30 × 40 cm. in area at 0° C., what will be its area at a temperature of 25° C.? *Ans.* 1201.38 sq. cm.

6. 100 c.c. of mercury at 0° C. is heated to 100° C., what will its volume be then? *Ans.* 101.8018 c.c.

7. The sum of the lengths of the steel rods in a gridiron pendulum is 236 cm. How long must the brass rods be? *Ans.* 136.63.

8. 275 c.c. of gas at 18° C. will have what volume when the temperature is reduced to 0° C.? *Ans.* 258 c.c.

9. If 200 c.c. of gas at 5° C. and at a pressure of 76 cm. be subjected to a pressure of 73 cm. and a temperature of 25° C., what will its volume be? *Ans.* 223.2 c.c.

10. 1500 c.c. of air at 12° C. and under a pressure of 74 cm., will have what volume under standard conditions? *Ans.* 1399.03 c.c.

11. What is the weight of a liter of air when the pressure is 80 cm. and the temperature is — 10° C.? *Ans.* 1.413 g.

12. If 100 c.c. of air under standard conditions has its pressure changed to 73 cm., to what temperature must it be changed that its volume may not be changed? *Ans.* — 10.78° C.

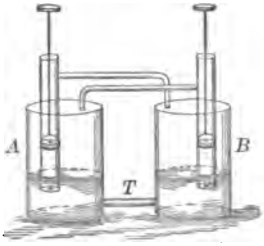
186. Transferrence of Heat.

All bodies of matter of which we have any knowledge contain heat. Such bodies, whatever their temperature may be, are constantly sending off heat to other bodies or into the space about them. When two bodies have the same temperature there is no apparent flow of heat between them, for they give and receive alike.

This may be illustrated by a water analogy, as shown in Fig. 127, the height, or head, being taken to represent temperature. *A* and *B* are two vessels filled with water to the same level. If water now be pumped at an equal rate from each vessel into the other, there will still be no difference of level in the two vessels. This roughly represents the relation of two bodies at the same temperature.

If, however, the water stands higher in one of the vessels, then there will be a flow through the tube *T*, and the pumps will continue as before. The excess of flow from the higher to the lower level will continue until the head in each vessel is the same. This roughly represents the relation of two bodies which have different temperatures. A hot body gives an excess of heat to a cooler one until their temperatures are equal.

Fig. 127.



Water analogy of exchange of heat between two bodies.

There are three ways by which heat energy is transferred. These are *conduction*, *convection*, and *radiation*.

187. Conduction.

In conduction heat travels through a body from molecule to molecule. At points where the temperature is higher, the molecules are moving more rapidly. They communicate their motion to the adjacent molecules, they to others, and so on.

Conduction is the only method by which heat propagates itself from place to place.

188. Conductivity.

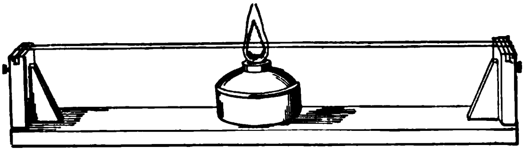
The ease with which heat travels varies greatly in different substances. All metals are good conductors, though some are much better than others, silver and copper being the best. Metals in a molten state are not as good conductors as when in a solid state. Most ordinary liquids and all gases are poor conductors.

Any substance that is a good conductor of electricity is also a good conductor of heat.

Experiment 35.

The difference in the conductivity of two metals may be shown by stretching two wires, say copper and iron, parallel and about 1 cm. apart. Rub the wires back and forth with a piece of beeswax and at the same time hold a flame beneath the wax. Numerous beads of the wax will cling to the wires. When cool, let a flame play against the wires at one point. The wax will melt and flow much farther from the flame on the copper than on the iron wire. At the point where the flame is applied, the iron will become red-hot before the copper does, because the heat cannot so readily leave that point on the iron and also because the capacity of iron for heat is less than that of copper.

FIG. 128.



Conduction.

The relative conductivity of a number of important substances is given in the table below.

Silver	1.096	Marble	.005
Copper	1.041	Glass	.0025
Aluminum	.344	Water	.0014
Zinc	.303	Cork	.0007
Iron	.167	Hydrogen	.0004
Mercury	.0152	Air	.000056

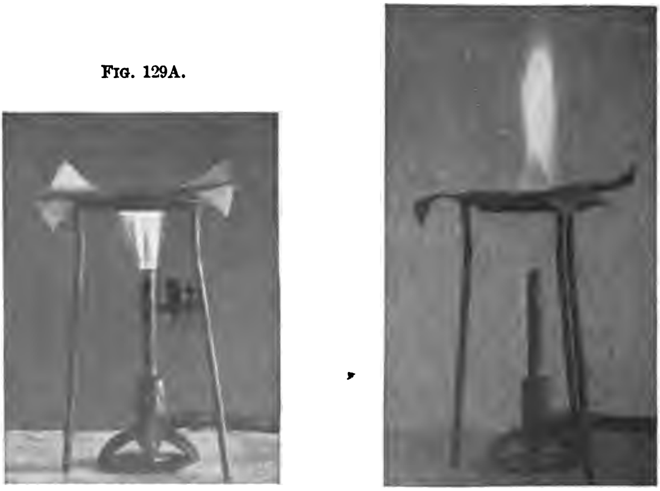
189. Uses of Good and Poor Conductors of Heat.

When a fire burns within a stove, the heat is distributed by conduction through the whole body of the stove and prevents an excessive heating at any one point.

The cylinders of some gasoline engines are surrounded by numerous flanges into which the heat passes by conduction and is then carried away on the air.

FIG. 129A.

FIG. 129B.



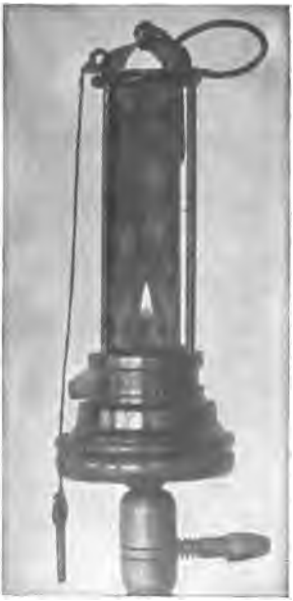
The flame and the wire screen.

If a wire screen of fine mesh is held over the flame of a Bunsen burner, the flame will be depressed, Fig. 129A. If, however, the gas is ignited above the screen, the flame will not pass down through the gauze to the gas below. If the wire becomes red hot, it no longer separates the flame from the gas on the other side.

The reason for this is found in the fact that the gas will not begin to burn until its temperature has been raised to a point called the kindling point. The wire gauze, being a good conductor, prevented, for a time, a high temperature at any one point.

This principle is applied in the construction of Davy's safety lamp, Fig. 130. This lamp may be carried into a mine where there are explosive gases, and the gas may burn and splutter within the lamp but an explosion in the mine is prevented for reasons given above.

FIG. 130.



Davy's safety lamp.

Frequent use is also made of poor conductors. Cork, as the table shows, is a very poor conductor. For this reason it is often ground into small pieces and packed between the walls of refrigerators to keep out the heat. A woolen garment, which is itself a poor conductor, contains a great deal of air which is a very poor conductor. Such a garment is most effective in preventing the passage of heat to and from the body. Wood is a poor conductor and for this reason is used on handles of many tools and utensils.

Numerous illustrations of this kind might be given.

190. Convection.

When heat is conveyed from place to place by the motion of the body which contains the heat, the process is called *convection*. For example, heated air or water will be set in motion by the force of buoyancy and will carry their heat with them.

191. Ventilation.—Convection in Gases.

Ventilation is effected chiefly by convection currents of air. In some buildings the air in a ventilating chimney is heated by a fire which is maintained for that purpose. The hot air rises and fresh air enters the room to take the place of that which ascends the chimney.

Hot-air furnaces are operated on this same principle. Fresh air from the outside of the building is made to pass about the hot furnace on its way into a room. The vitiated air of the room may at the same time be removed by a ventilating flue, and thus a constant supply of fresh warm air is provided.

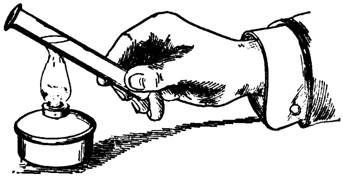
Steam and hot-water radiators will heat the air of a room by convection, but, unless special provision is made, the same air is kept in circulation within the room and no proper ventilation is provided.

Nearly all movements of the air are a result of convection. When the air is heated in any locality, it rises and other air flows in to take its place.

192. Convection of Liquids.

Water and most other common liquids are poor conductors of heat. It would be very difficult to heat water by conduction alone. A test tube filled with water and held over a flame, as shown in Fig. 131, may have the water boiling vigorously at the top while no perceptible heat is felt at the bottom.

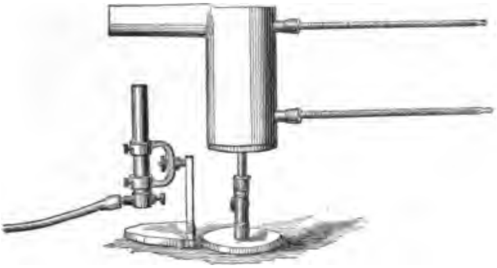
FIG. 131.



Water a poor conductor of heat.

When a vessel, like that shown in Fig. 132, is filled with water and heated by a flame placed beneath the projecting part, the water will boil at the surface but will not be heated in the lower part of the vessel. The temperature may be tested by two thermometers inserted in the sides of the vessel. The one near the surface may be near 100° C., but the one near the bottom will show no perceptible rise of temperature, though the surface water may have been boiling for some time.

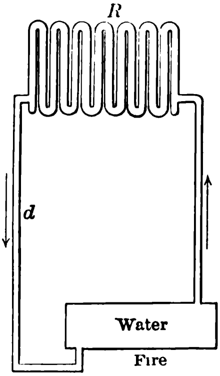
FIG. 132.



Illustrating the necessity of convection in heating water.

When a kettle of water is placed upon a hot stove, the heat is conducted through the bottom of the kettle to the water. The water next to the bottom is first heated and caused to expand. Then it rises because of the buoyant effect of the denser, cold liquid. Thus convection currents are set up which continually raise the warmer water to the top and permit the cooler water to sink to the bottom.

FIG. 133.



Transferring heat by convection.

This principle is applied in heating buildings by a circulation of hot water. As shown in diagram, Fig. 133, a coil of tubing may be placed in a furnace or stove in the basement, and the water in the tube when heated will rise to the radiator, *R*, and give off heat to the room. As soon as the water in the radiator is cooled, it will descend in the pipe *d*, be heated again, and rise with another quantity of heat.

193. Radiation of Heat.

Heat energy may be transferred on the ether from one body to another. A hot body will set up waves in the ether. When the wave falls upon another body, its energy is converted into heat again. The wave is not heat but it is caused by heat and may cause heat. This process of transmitting heat is called radiation.

FIG 134.

Radiator.

All the heat which we receive from the sun is transmitted in this manner. One may sit within a room near a window on a cold day and feel the warmth of the sun's rays while the air and the glass through which they come are very cold. The hands may be warmed near a hot stove even when the air between the hands and the stove is at a temperature below zero. Heat, as such, is not transmitted.

Waves produced by heat obey the same laws as waves of light, and travel with the same speed through ether.

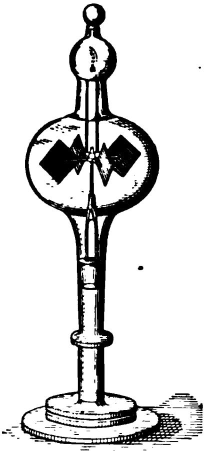
194. Absorption of Heat.

Some substances readily absorb the waves which fall upon them. Lampblack is an example of a good absorber. If the bulb of a thermometer is covered with soot or lampblack, it will show a higher temperature in a warm room than one near by which is not so treated. Dark colored substances, as a rule, will both absorb and radiate heat better than white ones. Much also depends on the character of the surface. Polished surfaces are poor absorbers and also poor radiators, while rough surfaces will be good in both. Any body which is a good absorber will also be a good radiator, and if a good radiator, will be a good absorber.

195. The Radiometer.

The radiometer, Fig. 135, consists of a glass bulb within which are mounted light vanes of mica or aluminum upon a vertical axis which may rotate with very little friction. The vanes are covered with lampblack on one side only. Nearly all the air is pumped from the bulb so that the molecules which remain may move a considerable distance without colliding with each other. If some source of heat, a lighted match for example, be brought near, the vanes will move with their bright sides in advance. The black side absorbs heat more rapidly than the bright one, consequently the molecules of air rebound from the black side with greater velocity and produce a greater reaction. Since there are so few molecules of air in the bulb, equality of pressure at all points within the bulb is not readily restored.

FIG. 135.



The radiometer.

196. Transmission of Heat Waves through Substances.

When a substance will transmit heat waves freely without absorbing many of them, it is said to be *diathermanous* (*dia*, through, and *therme*, heat). That is, it lets heat through. When the substance absorbs a large part of the heat waves, it is called *athermanous.*

The most diathermanous substance known is rock salt, while water, glass and alum are good examples of athermanous substances.

The chief difference between light waves and heat waves is in their length. Light waves are much shorter than the heat waves. Light waves readily pass through such substances as water and glass, but these same substances will prevent the passage of the heat waves.

This principle greatly aids in warming the atmosphere. Dry air is diathermanous, but the atmosphere is always laden with water vapor, and water is athermanous. When the radiations from the sun pass through the atmosphere, many of the long waves are absorbed by the water vapor, while the short waves pass on through and heat the surface of the earth. The earth in turn then radiates only long waves which are again absorbed by the water vapor in the atmosphere.

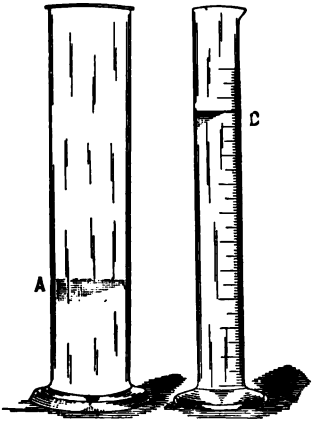
Green-houses and hot-beds are heated in a similar manner, the glass with which they are covered being transparent to light waves and athermanous to heat waves.

197. Specific Heat.

The specific heat of a substance is the ratio of the quantity of heat needed to raise its temperature one degree to the amount needed to raise the temperature of the same mass of water one degree.

Since one calorie will raise the temperature of one gram of water one degree, (§ 178), then the number of calories needed to raise the temperature of one gram of any substance one degree, will be the specific heat of that substance.

FIG. 136.



Difference of capacity.

198. Capacity for Heat.

Different substances vary greatly in the amount of heat needed to raise the temperature of equal masses to the same degree.

When a body has but little capacity for heat, its temperature will rise rapidly when heat is applied to it. When the capacity is large, the temperature will rise slowly. This may be illustrated by use of two vessels, as shown in Fig. 136. If the same amount of water is poured into each vessel, the height of the water in *B* will be much greater than in *A*, because the capacity of *B* is much less than that of *A*. In a similar manner we may think of temperature as rising or falling rapidly, and to a great extent, when heat is added to or taken from it, if its capacity for heat is small.

Water has a great capacity for heat. Since water is taken as the standard, the capacity of most other substance will be a fractional part of that for water.

Experiment 36.

For a rough observation of the difference in capacity, suspend a brass or lead weight of about 200 g. in boiling water. Weigh out the same mass of water and note its temperature. Note the temperature of the boiling water in which the brass is suspended. The brass will have the same temperature, say, 99° C. Lift the brass from the hot water and lower it into the 200.g. of water which has a temperature of, say, 16° C. Stir the water or lift the brass up and down by means of a string attached to it, until the brass and the water have the same temperature. This will be the case whenever the temperature of the water ceases to rise. All the heat which the water gained is assumed to come from the brass and the heat lost by the brass went to the water, and yet it is found that the temperature of the water rises very little while that of the brass falls a great deal. The thermal capacity of brass must therefore be small as compared with that of water.

199. Determination of Specific Heat.

There are several methods by which the specific heat of substances is determined. The one most commonly used is known as the method of mixtures. By this method a substance of known mass and temperature is mixed with water of known mass and temperature, the temperature of the substance being much higher than that of the water. The temperature of the mixture is then observed. The quantity of heat lost by the substance is gained by the water, and hence an equation can be formed with but one unknown quantity—the specific heat of the substance.

If M_w represents the mass of water, and t_w the number of degrees the temperature of the water was raised, then

$$Q_w = M_w t^\circ_w,$$

where Q_w represents the number of calories of heat received by the water.

The vessel which holds the mixture is called the calorimeter. It is usually made of light brass or copper and its temperature will change with the water which it contains. Hence it takes up some of the heat which should be in the water. The calorimeter may be reduced to its equivalent of water by multiplying its mass by its specific heat. This quantity is then called the *water equivalent* of the calorimeter. If M_c is the mass of the calorimeter and t° the change in temperature, then

$$Q_c = M_c t^\circ_c S_c,$$

where Q_c represents the number of calories of heat in the calorimeter, and S_c the specific heat of the substance of which the calorimeter is made. Then all the heat in the water and calorimeter would be expressed by

$$M_w t^\circ_w + M_c t^\circ_c S_c.$$

This would be the total amount of heat received from the substance that was mixed with the water.

The quantity of heat lost by the substance may be represented by

$$M_s t^\circ_s S_s,$$

where M_s is the mass, t°_s the change in temperature, and S_s the specific heat.

Since the quantity of heat gained by the water and calorimeter is equal to that lost by the substance,

$$M_w t^\circ_w + M_c t^\circ_c S_c = M_s t^\circ_s S_s,$$

$$\therefore\ S_s = \frac{M_w t^\circ_w + M_c t^\circ_c S_c}{M_s t^\circ_s}.$$

Suppose, for example, that 300 g. of some metal at 99° C. is mixed with 500 g. of water at 16° C. in a copper calorimeter whose weight is 75 g., and the resulting temperature is 18° C.

From this data the specific heat of the metal may be calculated by use of the equation given above. The specific heat of the copper in the calorimeter may be found in the table in the Appendix.

$$\text{Specific heat} = \frac{500 \times 2 + 75 \times 2 \times .095}{300 \times 81} = .0417$$

Problems.

1. If 10 *l.* of air at a temperature of 273° C. and a pressure of 76 cm. is set free in air under standard condition, with what force, greater than its own weight, is it buoyed up? *Ans.* 6.465 g.

2. If 66.6 calories will raise the temperature of 20 g. of mercury 100° C., what is the specific heat of mercury? *Ans.* .0333.

3. Find the water equivalent of a brass calorimeter which weighs 85 g. *Ans.* 7.98 g.

4. How much will the temperature of 40 g. of iron be reduced if sufficient heat is taken from it to raise the temperature of 14 g. of water 3° C.? *Ans.* 9.94° C.

5. A copper calorimeter weighs 42.5 g. and contains 275.3 g. of water at 8° C. 102 g. of water at 99° C. is added. What is the resulting temperature? *Ans.* 32.34° C.

6. Calculate the specific heat of lead from the following data:

Mass of water in calorimeter	400 g.
Temperature of same	10° C.
Weight of copper calorimeter	50 g.
Weight of lead	300 g.
Temperature of same	98° C.
Temperature after mixture	12° C.

Ans. .0314.

7. If one kilogram of iron and the same mass of water are each receiving heat at the same rate, how hot will the water be when the iron is 500° C. (red hot)? *Ans.* 56.2° C.

8. How many times as much heat may be stored in a jug of water as in a slab of marble of the same mass and temperature? *Ans.* 4.63.

200. Latent Heat.

While ice is melting its temperature does not change. When water is boiling its temperature remains constant, near 100° C. In changing the ice to water or the water to steam, a great deal of heat is required, but the temperature does not change. This is true of all substances when they are changed from solid to liquid or from liquid to gas, though the phenomena are not so noticeable as in the case of water.

The heat required to produce this change of state is called *latent heat.* The term *latent* means *hidden* or *concealed.* It originated at a time when the nature of heat was not well understood. The heat is not latent except in the sense that it does not show on the thermometer. It is expended, not in raising the temperature, but in separating the molecules. The energy of the heat is then in the form of potential energy, and when the gas changes back to a liquid, or the liquid to a solid, all this energy is returned again in the form of heat.

201. Latent Heat of Fusion.

The number of calories of heat required to fuse, or melt, one gram of a substance after it has been heated to its melting point, is called the latent heat of fusion. In Table VIII of the Appendix is given the approximate latent heat of a number of substances. It should be noticed that the latent heat of water, both in fusion and vaporization, is much greater than that of the other substances.

Experiment 37.

The following experiment illustrates the fact that a large quantity of heat is needed to melt ice, and also gives the approximate value of its latent heat of fusion.

200 g. of water at 22.5° C. is placed in a suitable vessel or calorimeter. 20 g. of dry crushed ice is put into the water and stirred with a thermometer until it is all melted. The resulting temperature, as found by trial, is 13° C.

The water is much cooler because sufficient heat left it to melt the ice and raise the temperature of the water, which resulted from the melting of the ice, from 0° C. to 13° C. Hence we can make an equation with what the water lost on one side, and what the ice, and the water from it, gained on the other side. Then, if L represents the latent heat,

$$\begin{aligned} 200 \times 9\tfrac{1}{2} &= L \times 20 + 20 \times 13 \\ \therefore L &= 82 \text{ (a number a little too large).} \end{aligned}$$

Careful experiments show that the latent heat of fusion of ice is nearly 80 calories.

This is a great advantage in nature. Bodies of ice and snow melt slowly because each gram of their mass must receive 80 calories of heat before they can be converted into water. Water, on the other hand, may be reduced to a freezing temperature, but it will not freeze until it has lost 80 calories per gram.

202. Latent Heat of Vaporization.

When a liquid reaches the temperature at which it begins to vaporize, its temperature becomes constant and the added heat is expended in separating the molecules still farther from each other. Thus the liquid is converted into its vapor, and in that form contains as much more energy as was in the heat expended in producing the change.

When the vapor is condensed, all this energy is returned in the form of heat.

The latent heat of vaporization of water is very large, being about 536 calories for each gram.

Experiment 38.

The experiment described below will give an idea of the large amount of heat required to vaporize water and will also give an approximate value of its latent heat of vaporization.

Cool some water to a temperature about 15° C. below the temperature of the room, that the heat absorbed from the room in the first part of the experiment may equal the amount radiated from the water in the latter part. Pour about 300 g. of the water into a vessel which is used as a calorimeter, and weigh carefully.

Meanwhile have some water heated in a boiler. Attach a rubber tube a foot or more long to the outlet of the boiler. To the end of this tube attach a glass trap to catch any steam which may condense before it reaches the water. Attach a short piece of tubing to the lower end of the trap and let this project about 2 cm. beneath the water. Take the exact temperature of the water in the calorimeter, then let steam pass into it until the temperature rises about 30 degrees. Stir the water constantly with the thermometer. Then lift out the steam tube and note the exact temperature.

The original weight of the water plus the water equivalent of the calorimeter, multiplied by the rise in temperature, must be equal to the heat received from the steam, which is the increased weight of the water multiplied by the *latent heat* of the steam plus the same mass of water multiplied by the fall of temperature after the steam is condensed.

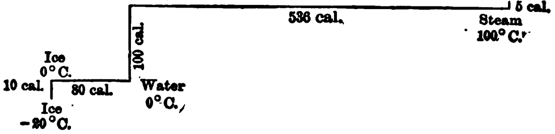
203. Heat needed to change Water from Ice below 0° C. to Steam above 100° C.

Since, in case of water, the thermal capacity as well as the latent heat of fusion and vaporization are very large, it requires a great deal of heat to convert ice into steam.

The specific heat of both ice and steam may be roughly taken as .5 (see Appendix VII). That is, in heating ice which is below zero, or steam which is at or above boiling point, it requires only about half as much heat as would be required to produce the same change of temperature in an equal mass of water.

The whole range of changes as well as the amount of heat required per gram may be represented by the diagram, Fig. 137, where one gram of ice at — 20° C. is changed to steam at 110° C. The vertical lines represent rise of temperature while the horizontal lines represent latent heat.

FIG. 137.



Quantity of heat needed to effect a change in state and temperature of water.

By considering the process step by step it is seen that 10 cal. are first used in raising the temperature of the ice to 0° C.; then 80 cal. more will change ice at 0° C. to water at 0° C.; 100 cal. will raise the water to 100° C., the boiling point; 536 cal. will convert the water at 100° C. to steam at the same temperature; and 5 cal. more will heat the steam to 110° C.

In all, then, 731 cal. will be needed to effect the change. For any given number of grams, the heat needed would be that many times 731.

It is thus easy to calculate the amount of heat needed to produce the change between any two points that may be selected on the diagram, or the amount of heat given off when the process is reversed. Thus, suppose 40 g. steam at 100° C. is condensed and cooled to water at 30° C. The heat taken from the steam and water must be $40\,(536 + 70) = 24{,}240$ calories.

204. Liquefaction of Solids.

Each crystalline substance will begin to melt at a definite temperature, known as its melting point.

The melting points of a number of substances are given in Appendix IX.

Most substances expand on melting and contract when they are changed from a liquid to the solid state. A few substances,—water, bismuth, antimony, type metal, cast iron, and a few others, contract when they are melted and expand when they are solidified. Metals of this character are useful in castings, for they will completely fill the mold when they solidify. Exact castings of gold and silver cannot be made because these metals contract when they solidify.

Water expands from 1 to 1.0907 at the moment it freezes; that is, a little more than one-twelfth.

Substances which contract on melting will have their melting points lowered by pressure, and those which expand will have their melting points raised. This is what we would expect, for the increased pressure either helps or hinders that which the heat must do to effect a change of state. The difference of melting point due to a change of pressure is small. For an increase of one atmosphere—14.7 lbs. to the square inch—the melting point of ice is lowered only .0072° C.

Alloys usually melt at a lower temperature than the melting point of any of the metals that compose them. Rose's fusible metal, for example, composed of 4 parts bismuth, 1 part tin, and 1 part lead, melts at 94° C.

When a body begins to melt, the temperature remains constant until the whole amount of latent heat necessary to convert it to a liquid has been received.

As soon as the body is all melted, its temperature will begin to rise. When part is liquid and part solid, the heat needed to liquify the solid part will come from the liquid, and thus the temperature of all will be kept at the melting point until all is melted.

That this may be shown by experiment, it is necessary that the heat be applied slowly and that the solid and its liquid be closely mingled.

205. Vaporization.

Many liquids and some solids will under proper conditions change to a vapor.

All bodies of which we have any knowledge contain more or less heat. Their molecules then are in more or less rapid motion. Some of the molecules at the surface of a body leap beyond the range of attraction of others near them and make their escape from the body.

When this takes place slowly at the surface of a liquid, it is called *evaporation.*

When a solid, such as camphor, arsenic, iodine, and snow at a temperature below 0° C., passes directly, without melting, into a state of vapor, it is called *sublimation.*

When the temperature of a liquid is raised to the boiling point, parts of the liquid beneath the surface, at the point where the heat is applied, are converted into vapor. This vapor, rising through the body of the liquid, causes a disturbance known as *boiling* or *ebullition.*

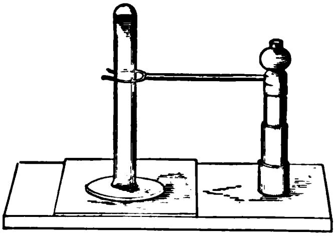
206. Evaporation.

Several different conditions which modify the rate of evaporation may be illustrated by Experiment 39.

Experiment 39.

Fill a slender test tube with water and invert it, as shown in Fig. 138, so that its open end rests on a circular piece of blotting paper about 6 cm. in diameter. Water will escape from the tube only as fast as it evaporates from the blotting paper. A pin hole in the center of the paper will permit air to enter the tube as the water runs out. The paper should rest on a glass plate so that none of the water may be soaked up.

FIG. 138.



Evaporimeter.

By calculating the volume of the tube and the area of the paper exposed, it is possible to determine the rate of evaporation per unit area.

By placing this apparatus in still air, then in moving air; in cold, then in warm air; in dry, then in moist air, the rate of evaporation will be very different.

Better results will be obtained if two sets of the apparatus are used at the same time under different conditions.

By experiments similar to the one just described, the following laws have been derived:

(1) *Evaporation increases as the temperature rises.*

(2) *The amount of material evaporated is proportional to the area of the surface exposed.*

(3) *The rate of evaporation is increased by a constant change of air at the evaporating surface.*

(4) *The rate of evaporation is increased by a decrease of pressure.*

The theory of evaporation would lead us to believe that these laws were correct, but we have many experimental proofs in our every-day experience. A wet cloth, for example, will dry more rapidly when the air is warm, when the air is moving, and when the cloth is spread out so as to expose a large surface. The effect of decrease in pressure is illustrated by the use of "vacuum pans" in which the pressure is partly removed by pumps. The water in syrups will then evaporate rapidly without being heated to the boiling point.

207. Boiling, or Ebullition.

Each liquid begins to boil at a definite temperature, known as its boiling point.

The boiling point of each liquid will be the same under the same conditions. In Appendix X may be found the boiling point of a number of substances on the condition that the substance is pure and under a standard pressure.

If a liquid contains salts in solution its boiling point is raised. If gases are in solution, the boiling point is lowered.

Experiment 40.

Boil some soft water in a test tube and note its temperature. Add to the water a considerable quantity of table salt, boil, and note the change in temperature.

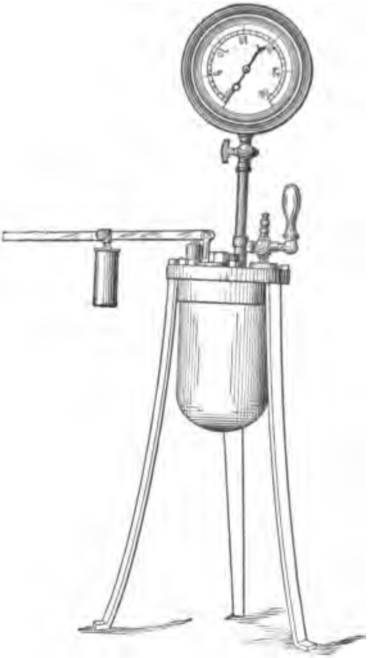
It is also found that when the inner surface of the containing vessel is smooth, the boiling point is higher than when it is rough. This is probably caused by the greater adhesion to the smooth surface.

The boiling point is greatly changed by a change in the pressure on the surface of a liquid. When a liquid is being converted into a vapor, it exerts a pressure known as its *vapor pressure.* When the vapor pressure is just equal to the air pressure, or other pressures, upon it, the boiling point has been reached. The vapor pressure increases as the temperature rises. As we might expect, then, any increase of pressure on a liquid will raise its boiling point, and decrease of pressure will lower the boiling point. The pressure upon a liquid must be opposed by an equal vapor pressure before a liquid will boil.

The vapor (steam) which results from boiling the water, occupies 1690 times as much space, under standard pressure, as the water did. When water is boiled in a steam boiler, or other closed vessel, the pressure becomes greater and greater, and so the temperature of the water rises higher and higher. Under a pressure of two atmospheres, water boils at about 120° C., under ten atmospheres, 180° C.

The apparatus shown in Fig. 139 is a brass boiler to which an indicator is attached to show the pressure of steam within. The bulb of the thermometer rests in a small brass cup which is partly filled with mercury and which extends down into the steam. The temperature and pressure will be observed to rise or fall together.

FIG. 139.



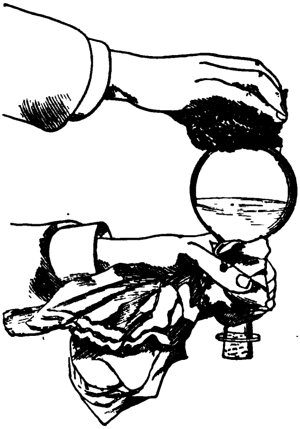
Pressure increases the boiling point.

Experiment 41.

The lowering of the boiling point by diminished pressure may be shown by the device illustrated in Fig. 140. Fill the bottle about half full of water, and heat it till the water boils. Remove the flame and cork the bottle tightly. Invert and pour cold water over the bottle.

The pressure is thus diminished by the condensation of the steam, and boiling will continue even when the temperature is reduced to 50° C. or lower.

FIG. 140.



Decrease of pressure lowers the boiling point.

The change in boiling point due to changes in atmospheric pressure at any given locality is not large and is not usually noticed. A change of 2.7 cm. of mercury in the pressure of the atmosphere causes a change of one degree in the boiling point. Appendix XI is useful in finding the true boiling point at the pressures there given.

208. Effects of Altitude on Boiling Point.

Since the atmospheric pressure decreases as the altitude increases, the boiling point of a liquid is perceptibly less at a high elevation. At Mexico, for example, water boils at about 92.3° C.; at Quito, 90.1° C.

The approximate altitude of a point may be determined by allowing 960 feet for a change of 1° C. in the boiling point.

209. Cooling Effect of Vaporization.

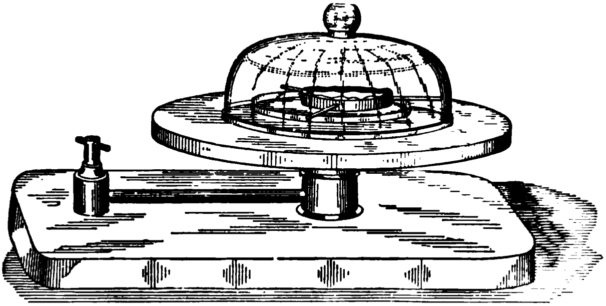
A great deal of heat is required to convert a liquid to a vapor (§ 202). This heat is carried away with the vapor. For this reason it is not possible to heat a liquid any hotter than its boiling point. The more heat it receives, the more liquid will be vaporized. Thus a boiling liquid is cooled as fast as it is heated.

This is the reason certain vegetables, potatoes for example, cannot be cooked by boiling in water on a high mountain.

It is the heat that cooks, and water, there, reaches its boiling point, in an open vessel, much below the boiling temperature at sea-level.

Ordinary evaporation is also a cooling process, and for a similar reason a sensation of cold is experienced when any volatile liquid is made to rapidly evaporate from the surface of the skin. Moving air seems cooler because it increases evaporation from the surface of the body.

FIG. 141.



Water frozen while it boils.

Artificial ice is commonly made by evaporating liquid ammonia in pipes which surround vessels of water. The liquid ammonia is kept under great pressure to prevent its evaporation. When it is used, the pressure is removed. The heat from any body near by then flows into it and converts it to a vapor. Thus the water loses its heat and is changed to ice.

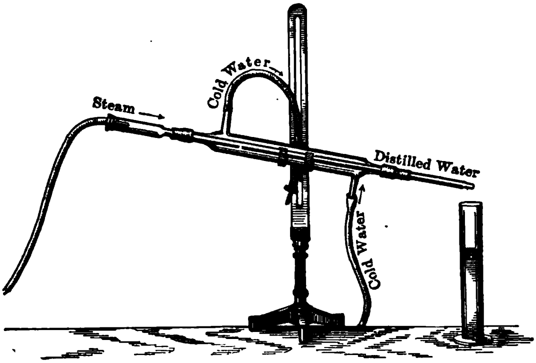
210. Condensation.

A change of the vapor back to a liquid is called condensation.

All the heat required to change a liquid to a vapor is given out again in condensation.

An apparatus for distilling water is shown in Fig. 142. The steam is passed into the inner tube. Cold water circulating about the tube carries off the latent heat of the steam, causing it to condense. The water resulting from the condensation is nearly pure and is called distilled water. This principle is employed in all distillation.

FIG. 142.



Distilling water.

211. Humidity.

The water vapor arising from lakes, seas, oceans, vegetation and moist earth, escapes into the air. Air at any given temperature is capable of holding a certain amount of vapor. When it has all it can hold, it is said to be *saturated.* If the air is warmed it will hold more moisture than when it is cold. The air, under ordinary conditions, may contain as much as five per cent. of water vapor.

The *humidity* is the amount of water vapor in the air. The *absolute humidity* is the amount of water in a unit volume of the air, as, for example, 20 grams per cubic meter.

The *relative humidity* is the amount of moisture—water vapor—in the air as compared to the amount which is required to saturate it. If the relative humidity is found, for example, to be 50 per cent., this means that the air contains one-half as much water as it would contain if it were saturated.

A liquid evaporates more slowly as the air about it becomes more nearly saturated. For this reason hot days are very oppressive when the air is humid. The perspiration evaporates slowly and the body is not sufficiently cooled.

212. Dew Point.

The *dew point* is the temperature at which the air is saturated. The least decrease of temperature will then cause some of the vapor to condense, and the least increase of temperature will give the air greater capacity for moisture.

The dew point may be reached either by adding more moisture to air, or by cooling the air until it is saturated.

Experiment 42.

Fill a bright nickeled cup to a depth of about 3 cm. with water. Note the temperature of the air in the room. Stir the water with the bulb of a thermometer and add a little crushed ice or snow from time to time until a mist is observed on the outside of the cup near the bottom. Note the temperature of the water at the moment the mist appears. Continue to stir and observe the temperature at the moment the mist disappears. These two temperatures should not be more than 2 degrees apart. The average is the dew point.

When the dew point and the temperature of the air are known, the approximate relative humidity may readily be found in Appendix XII.

213. Energy in Heat.

It has already been shown (§ 98) that a body of matter in motion possesses kinetic energy. This is the case no matter how small the body of matter may be. Heat is the motion of the molecules of which a body is composed. Hence a body which contains heat, also must contain a certain amount of kinetic energy. Energy, then, may be stored in a body in the form of molecular motion, or heat.

A body may be heated as a result of work done upon it, as when a piece of metal is heated by the stroke of a hammer;

when the motion of the hammer is arrested, its kinetic energy is converted mainly into molecular motion. Thus the motion of masses of matter may be converted into the invisible motion of molecules.

On the other hand, the reverse action may take place and molecular motion may be converted into the motion of masses of matter, as when steam causes the motion of the piston of an engine. Thus the energy in the moving molecules may be utilized in doing work.

214. Equivalent of Heat and Work.

It has been found that when 778 foot-pounds of work is done upon one pound of water, the temperature of the water is raised 1° F. This number—778—expresses the relation between heat and work, and is called the *mechanical equivalent of heat.* It is denoted by J, the first letter in the name of Dr. Joule. (See cyclopedia.)

The corresponding value of J in metric units is 41,870,000 ergs; that is, 41,870,000 ergs will raise the temperature of 1 g. of water 1° C. One calorie of heat is equal in energy to 41,870,000 ergs of work.

Suppose 2 pounds of water freely falls through a distance of 1167 feet, and, when its motion is suddenly arrested, suppose that all the energy is converted into molecular motion within the water. What would be the change in the temperature of the water?

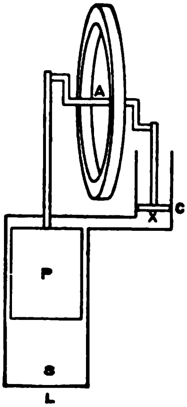
In this case the amount of energy will be 2334 foot-pounds, and since 778 foot-pounds will raise the temperature of 1 pound 1° F., 2334 foot-pounds will raise the temperature of 2 pounds 1.5° F.

Suppose it is desired to know how much the temperature of 1 g. of water would be raised if 1 kilogram-meter of energy is expended in increasing the molecular motion within the water. By reference to Appendix IV it is seen that there are 98,000,000 ergs in one kilogram-meter. Hence the temperature would be raised 2.34° C.

215. Heat Engine.

All engines in which heat is converted into mechanical motion may, in a general sense, be called heat engines. There is, however, a special application of this term to a kind of engine in which motion results from the alternate heating and cooling of an enclosed body of air. A diagram illustrating the principle of a heat engine is shown in Fig. 143. The air in the chamber *S* is heated by the fire at *L*. The air expands, as a result of the increased motion of its molecules. The plunger, *P*, fits loosely in the chamber *S* so that the expanding air may pass into the cylinder *C* and press upon the piston *X*. This will turn the shaft *A* through half a revolution and lower the plunger *P* to the bottom of *S*. The air displaced by *P* is then at the top of *S* where it is cooled and the outside air-pressure will then push the piston in *C* back to its first position. This operation is repeated and the engine will run as long as heat is applied.

FIG. 143.



Hot-air engine.

This kind of an engine requires very little attention and is serviceable where only small power is desired, as in pumping water or driving light machinery.

216. Gas Engine.

The gas engine derives its energy from the intense heat which results from the chemical union of a gas and the oxygen of the air. The principle is illustrated in the diagram, Fig. 144. When the piston *H* moves toward *O*, a partial vacuum is made in the cylinder, *S*. Air and gas then enter *S*, forming an explosive mixture. When the piston returns these gases are compressed and the two points *p* and *i* close an electric circuit from the battery *B*.

When the piston starts on its return stroke, the electric circuit is broken, causing a spark which explodes the gases. The intense molecular motion of the gases drives the piston to the other end of the cylinder. Thus there is a loading with explosive gases followed by an explosion at each alternate revolution of the fly-wheel.

Fig. 144.

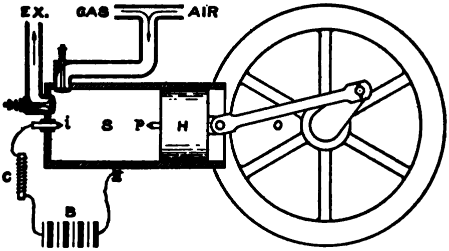


Diagram showing the principle of the gas engine.

217. Steam Engine.

The steam engine is the most reliable and the most serviceable of all heat engines.

It requires a large amount of heat to convert water to steam, and the molecular energy of the steam may then be conveniently converted into mechanical motion.

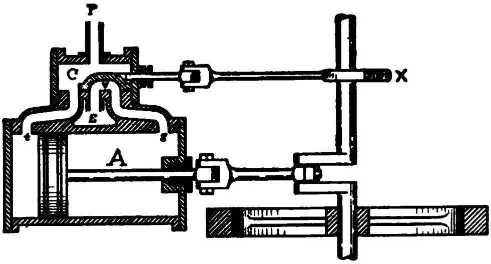
The essential mechanism of the steam engine is the device by which steam is made to exert pressure on one side of a piston and then on the other side, thus causing a reciprocating motion which in turn may cause a continuous rotation of a wheel.

Steam at a high pressure, and therefore very hot, comes from the boiler through a pipe *P*, Fig. 145, to the steam-chest *C*. From the steam chest the steam may pass through ports *s* and *t* to one end or the other of the cylinder *A*. The slide valve *V* alternately opens and closes these ports. The slide valve is moved by an eccentric, *X*. As you look at the diagram, the slide valve has been moved to the right.

The port *t* is thus opened and steam enters the cylinder, pushing the piston to the other end. The slide valve will then move to the left, closing the port *t* and opening *s*. The steam will then push the piston back. This operation is repeated for each rotation of the fly-wheel.

The slide valve may be adjusted so that it will admit steam to the cylinder only during a part of the stroke of the piston. This steam then expands and completes the stroke.

Fig. 145.



The steam engine.

After the steam has done its work it is forced by the returning piston out through the exhaust pipe *E*.

The piston is caused to move by the *difference* of pressure at the two ends of the cylinder. The greater this difference is, the more effective the steam-pressure will be. When the exhaust pipe is open to the air, there is a back pressure of about 14 pounds to the square inch on one side of the piston. If the steam pressure on the other side is, say, 74 pounds to the square inch, then its effective pressure is only 60 pounds to the square inch.

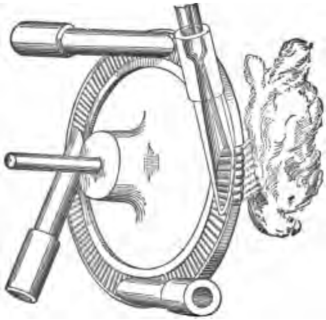
In many engines the exhaust steam is conducted to an air-tight chamber where a spray of water condenses the steam, and the back pressure on the piston is thus, for the most part, prevented. Such an engine is called a *condensing engine*.

Steam contains energy by virtue of the motion of its molecules, that is, its heat. In doing work it loses energy and consequently is cooled. The steam which is ordinarily exhausted from an engine, however, still contains a great deal of heat which is not converted by the engine into mechanical motion. To utilize the energy in steam more effectively, some engines are provided with two or more cylinders. The first is called the high-pressure cylinder and is constructed just like the one shown in Fig. 145. It exhausts, not into the air or a condenser, but into a second cylinder of the same structure but larger. In this second cylinder the steam expands, does work on its piston, and is further cooled. The steam exhausted from the second cylinder may be made to pass into a third one which is still larger and where further work will be done. This may be continued through four, five, or even six cylinders, the steam at last entering a condensing or vacuum chamber. Such engines are called *compound engines.*

218. Steam Turbine.

The molecular motion in hot steam may be converted into mechanical motion by directing jets of highly heated steam against a turbine wheel in the manner shown in Fig.

FIG. 146.



Steam turbine.

146. Such a machine is called a steam turbine. Continuous rotation is thus obtained directly, and the reciprocating motion of the ordinary engine is avoided.

Problems.

1. How much heat is needed to change 200 g. of ice at 0° C. to water at 0° C.? *Ans.* 16,000 calories.

2. How much heat is needed to change 55 g. of water at 100° C. to steam at 100° C.? *Ans.* 29,480 calories.

3. How much heat will be required to change 3 g. of ice at — 10° C. to steam at 120° C.? *Ans.* 2193 calories.

4. If 1 kg. of steam at 100° C is passed through a radiator and returns as water at 50°C., how much heat was taken from it? *Ans.* 586,000 calories.

5. What is the boiling point of water when the barometric pressure is 745 mm.? *Ans.* 99.445° C.

6. What is the approximate height of a point where water boils at 92.3° C.? *Ans.* 7392 feet.

7. If the temperature of air is 27° C. and the dew point is 15° C., what is the relative humidity? *Ans.* 48 per cent.

8. How much energy is required to heat one pound of water 12° F.? *Ans.* 9336 foot-pounds.

9. An iron ball weighing 10 kg. falls from the top of a building 30 m. high. If all the heat resulting from the concussion enters the ball, how much will its temperature be raised? *Ans.* .627° C.

10. What is the horse-power of an engine when a total pressure of 1000 pounds is exerted on the piston, there being 80 single strokes in a minute and the length of a stroke 30 inches. *Ans.* 6 horse-power, approximately.

CHAPTER XII.

SOUND.

219. Sound and its Source.

Sound is a sensation received through the organ of hearing. The sensation is caused by rapid vibrations in the air. Any body in a proper state of vibration will cause vibrations in the air surrounding it. When the air is in this state it may cause the sensation of hearing.

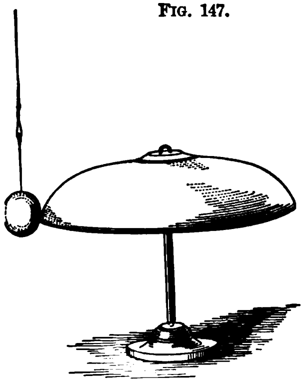
Sound is also defined as a vibratory motion which may affect the organ of hearing.

According to the former definition, there is no sound except when there is the sensation of hearing. By the latter definition there may be sound whether there are any ears to receive it or not.

220. Origin of Sound.

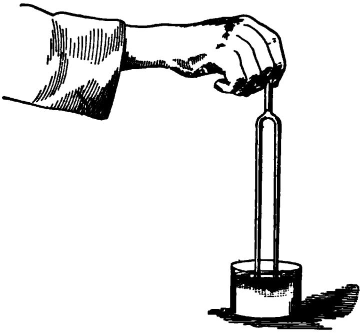
The disturbance which causes sound, or which, by the second definition, is sound, can in all cases be traced to a vibrating body.

FIG. 147.



To show the vibrations of a bell.

FIG. 148.



Touching the prongs of a vibrating tuning-fork to water.

When a bell is giving forth sound, its vibrations may be detected by touching it lightly with the finger or by holding against its edge a suspended ball of wood or cork (Fig. 147).

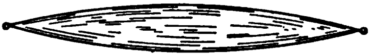
If the bell is firmly grasped, its vibrations and the sound cease at the same time. If while a tuning-fork is giving forth sound, the ends of the prongs are touched to the surface of water, a spray of water is thrown out on each side, showing that the prongs are rapidly vibrating. If a cord or wire, about one meter long, is tightly stretched between two supports, its vibrations may be plainly seen and the resulting sound will continue as long as the cord vibrates. Thus in every instance when a sound is heard, its cause can be traced to some body in a state of vibration.

221. Kinds of Vibrations.

Vibrations are of three kinds—*transverse*, *longitudinal*, and *torsional*.

If a cord is tightly stretched and then plucked in the middle, it will vibrate as shown in Fig. 149. Such a vibration is called transverse, because the direction of the motion is at right angles to the length of the cord. The vibrations of a tuning-fork, a bell, piano wires, and all stringed instruments, are examples of transverse vibrations.

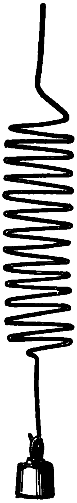
FIG. 149.



Transverse vibrations.

A vibration is called longitudinal when its motion is in the direction of the length of the vibrating body. If the coil shown in Fig. 150 is drawn toward either support and then released, the resulting vibrations will be longitudinal. Solid

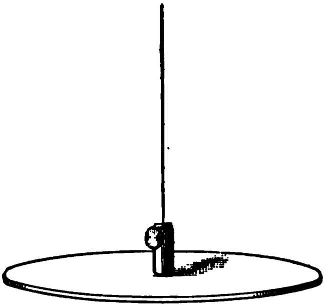
FIG. 150.



Longitudinal vibrations.

bars of brass or steel may be made to vibrate lengthwise by clamping them firmly at the center and drawing a wet cloth or a rosined piece of leather along the bar. Such vibrations are very rapid and a distinct musical sound is produced.

FIG. 151.



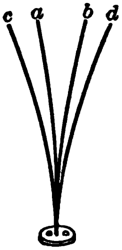
Torsional vibrations.

Torsional vibration is caused by the twisting and untwisting of a cord, wire, or other body. In Fig. 151 a steel wire supports a circular disk. If the disk be made to rotate through a few degrees, the wire will be twisted. In untwisting, the disk is made to rotate in the opposite direction. This rotation does not cease until the wire is twisted in that direction. The wire again untwists and thus a torsional vibration is continued.

222. Simple Harmonic Motion.

When the particles of an elastic body are vibrating, they move according to Hooke's law (§ 68), that is, the force tending to bring the particle to a position of rest varies directly as the distance from that position. Vibrations of this character are called *simple harmonic motion*.

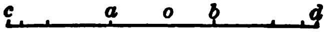
FIG. 152.



If an elastic rod is rigidly fastened at one end, and the other end is drawn aside to *a* (Fig. 152) and released, a certain force will restore the rod to its position of rest. Its momentum carries it on to *b*, where the force again tends to restore it to the position of rest and the rod is returned to *a*. If the rod is drawn aside to *c*, twice the distance, the force will be twice as great and the rod will vibrate between *c* and *d* in the same time as between *a* and *b*.

Let the path of a vibrating particle be represented by a line (Fig. 153). Let the line be divided into spaces over which the particle will move in equal intervals of time. The longest space will be at the center, *ab*, where the particle moves most rapidly. The spaces become less and less toward the ends where the particle comes to rest, and then begins its return trip.

FIG. 153.



The path of a body moving in simple harmonic motion.

The distance from the center of the line, *o*, to *c* or to *d* is called the *amplitude* of the vibration. The time required for a vibrating particle to move from any point back to the same point, going in the same direction, is a *period.* The number of complete vibrations in a second is the *frequency.*

Vibrating bodies which produce musical sounds execute simple harmonic motions, and hence the name.

The nature of this kind of motion may be observed by the following experiment.

Experiment 43.

Suspend a ball from a long thread so that the ball nearly touches the top of a table. Cause the ball to revolve in a horizontal circle. View its motion from a distance, placing the eye on a level with the surface of the table. The eyes should be nearly closed so that the ball may be only dimly seen. The ball will appear to move back and forth in a straight line in simple harmonic motion.

223. Waves.

When any part of an elastic body is in a state of vibration, it communicates its motion to adjacent parts, these to others, and so on. Thus a motion, called a wave, may be transmitted from one point in an elastic medium to another. A wave, then, may be defined as *the form of a medium while it is transmitting simple harmonic motion.*

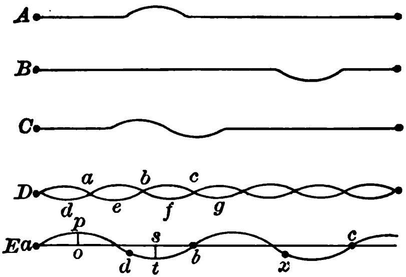
The motion of the particles upon which a wave is being transmitted may be either *transverse*—that is, at right angles to the direction of the wave—or *longitudinal*—that is, in the same direction as the wave. Waves moving on the surface of water or along a flexible cord are examples of transverse waves. Sound waves moving through the air are examples of longitudinal waves (§ 224).

Experiment 44.

Stretch a flexible cord or a coil of brass wire, about 12 or 15 feet long, loosely between two supports. The coil is preferable. By a stroke of a stick near one end of the coil, or by a rapid motion of the hand holding one end of the coil, various forms of transverse vibrations may be produced. By compressing a section of the coil lengthwise and releasing it, a longitudinal wave may be produced.

If the cord is struck from above, near one end, a depression, called a *trough*, *B*, (Fig. 154) will move along the cord to the other support, where it will be reflected as an elevation, called a *crest*, *A*. If the cord is struck from above and then from below in quick succession, both the trough and the crest, constituting a complete wave, may be made to pass over the cord *C*.

FIG. 154.



Waves.

If one end of the cord is taken in the hand and rapidly vibrated, it may be made to take the form shown in *D*. The points *a*, *b*, and *c* are called *nodes*. These are points where a trough and a crest, moving in opposite directions, meet. The one neutralizes the other and hence there is no motion. Between the nodes are the *ventral segments*, or *antinodes*—*d*, *e*, *f*, *g*. These segments consist of troughs and crests following each other in quick succession.

A *wave length* is the distance from any particle to the next particle in the same stage of vibration. Thus in Fig. 154 *E*, *a* to *b*, *b* to *c*, and *d* to *x*, are wave lengths.

Two particles in a wave are said to have the same *phase* when they are moving in the same direction, with the same velocity, and are similarly located. Thus, *d* and *x*, or *a* and *b*, Fig. 154 *E*, have the same phase.

The distance *op* or *st* is the *amplitude*.

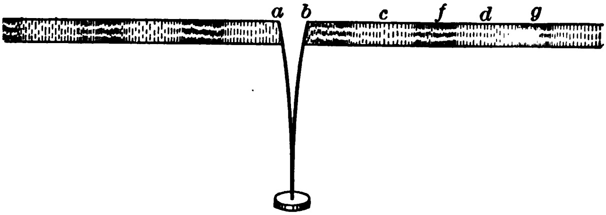
224. The Nature of Sound Waves in Air.

The great medium upon which we must rely for nearly all the waves which produce the sensation of sound is the air.

Sound waves in the air are composed of *condensations* and *rarefactions*. They are longitudinal vibrations.

Suppose one end of the steel rod (Fig. 155) is rapidly vibrating between *a* and *b*. In moving toward *b*, the particles of air on that side are crowded or condensed. This crowded portion is called a condensation. These particles crowd others adjacent to them, these the next, and so on. Thus, the condensation moves out from the vibrating body.

FIG. 155.



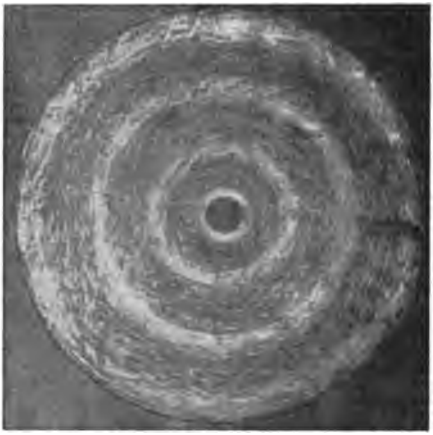
Condensations and rarefactions.

When the rod moves from *b* to *a* the particles of air on that same side are moved farther apart—that is, the air is rarefied. This condition of the air is called a rarefaction.

The adjacent particles then move toward the rarefied portion and thus the rarefaction also moves out from the vibrating body.

Similar conditions are alternately being produced on the other side of the rod. When there is a condensation at *b*, there is a rarefaction at *a*, and vice versa.

FIG. 156.



Cross section of spheres of sound waves.

A wave length here is, as before, the distance between any two particles in the same stage of vibration, as, *c* to *d*, or *f* to *g*.

All longitudinal waves, in whatever medium, are transmitted in this manner.

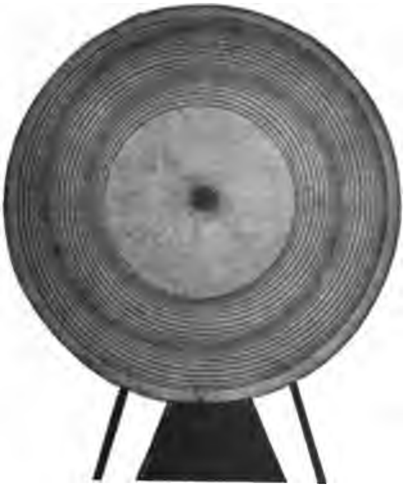
When a vibrating body is surrounded by air only, the waves move out in all directions, forming concentric spheres. A cross section of such a sphere may be represented by Fig. 156.

Experiment 45.

Mount a Crova's disk upon a turning table, as shown in Fig. 157. This disk is made of cardboard, and upon it are drawn lines which are nearly concentric circles. The portion of the disk upon which the lines are more closely crowded forms a spiral about the center.

When the disk is slowly rotated, the condensed and rarefied portions will appear to follow each other from the center out to the end of the disk.

FIG. 157.



Crova's disk.

225. The Media for Sound Waves.

Sound waves may be transmitted through solids, liquids, or gases, though the common and almost exclusive medium is the air—a gas.

Experiment 46.

The transmission of sound waves in a solid may be illustrated by placing a watch upon a long pine stick or board, and pressing the ear against the other end. The tick of the watch may be plainly heard.

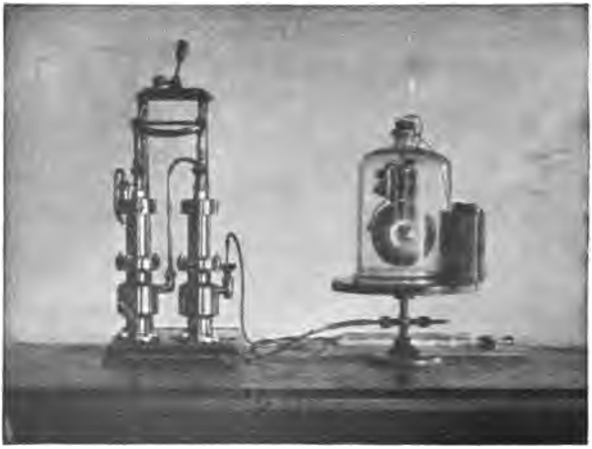
The same principle may be illustrated by the wire telephone, in which a wire is tightly stretched between two sounding boards which may be a hundred feet or more away from each other. A conversation may be satisfactorily carried on by use of such an instrument.

(Minute directions for making this telephone may be found in the "First Book of Physics.")

Experiment 47.

To show that sound waves are not transmitted in a vacuum, prepare an apparatus like that shown in Fig. 158. The receiver is closed at the top with a rubber stopper. Two short brass rods fit tightly in holes through the stopper. At the lower end of one of the rods is a hook from which a large electric gong is suspended. The bottom of the other rod is connected by a copper wire to the insulated post of the gong. A battery attached to the tops of the rods causes the gong to ring.

FIG. 158.



Vibrating body in a vacuum.

Pump the air as completely as possible from the receiver and attach the battery to the gong.

226. Velocity of Sound.

The velocity of sound is different in different media or under different conditions of the same media.

The more elastic a body is, the more rapidly it will transmit waves.

This is as might be expected, for the more elastic a body is, the more promptly its particles will regain their equilibrium after being strained by the passage of a wave.

The more dense a body is, the more slowly a sound wave will pass through it, because the inertia of a greater mass of matter must be overcome.

The relation of velocity of sound waves to the elasticity and density of the medium may be exactly stated as follows:

The velocity of sound waves varies directly as the square root of the elasticity of the medium and inversely as the square root of the density.

This may be stated by the formula

$$V = \frac{\sqrt{e}}{\sqrt{d}}$$

The velocity of sound waves in air at 0° C. is 332 m. or 1090 feet per second.

When the temperature of the air rises, the elasticity increases and, consequently, the velocity increases. It is found that the correct velocity at any temperature may be obtained by adding .6 m. or 2 feet for each increase of 1° C. Thus, at 20° C. the velocity of the sound wave in air is 344 m., or 1130 feet.

In oxygen gas, sound travels more slowly than in air, because oxygen is denser than air. Hydrogen is only one-sixteenth as dense as oxygen, and hence sound waves pass through it four times as fast.

The velocity of sound through liquids and solids is usually much greater than in gases because, although the density is greater, the elasticity is much greater.

The velocity of sound waves in various substances is given in the table below:

Air, 0° C.	332 m.
Hydrogen, 0°	1286 m.
Oxygen, 0°	317 m.
Water, 4° C.	1400 m.
Copper	3500 m.
Brass	3500 m.
Iron	5090 m.

227. Reflection of Sound.—Echoes.

Sound waves, like other waves, are reflected, bent back or aside, when their path is obstructed by any surface. The reflected waves are not intense, because a part of the energy is communicated to the reflecting surface.

If the path of the waves is perpendicular to the reflecting surface, the reflected waves will return in the same path.

If the surface is large and at a considerable distance from the source of the sound, the reflected sound, called an *echo*, may be clearly distinguished from the original sound. The side of a large building, a cliff, or a dense woods, are surfaces from which echoes are often heard.

If, for example, one should stand at a distance of 550 feet in front of a large barn and should utter a sharp sound, the sound waves must travel to the barn and back again before the echo can be heard. The time required for this would be one second on a day when the velocity of sound is 1100 feet per second.

A word or short sentence of five syllables may be distinctly uttered in one second, and so the whole word or sentence may be distinctly heard in the echo at that distance. At a greater distance a longer word could be used.

If the distance is less that 100 feet, the sound returns so quickly that the echo is not readily distinguished from the original sound.

The voice of a speaker can be more distinctly heard within a room than in the open air, because the words which are reflected from the walls reach the ears of the audience in nearly the same time as those directly from the speaker. In some large halls and churches, however, the size and shape of the room are such that the echoes and the original sound reach the ear at slightly different times, causing a very unpleasant confusion of sound.

Multiple echoes are produced when sound waves are reflected back and forth between two reflecting surfaces, as between the parallel walls of a large room. One standing between the walls would hear the sound each time the waves pass.

When the crash resulting from a stroke of lightning is reflected from the clouds or back and forth between banks of air of different density, we hear what is called the "rolling of thunder."

When the sound waves are reflected from a concave surface they meet at a point called the focus. Feeble waves from a large area may thus be made intense at the focus. When there is a curve in the walls of a hall or church, a certain point may be found where the speaking or singing may be most distinctly heard. Famous "whispering galleries" have been constructed on this principle.

228. Musical Sounds.—Noise.

We usually distinguish two classes of sounds—*musical sounds* and *noises.*

Musical sounds are produced by any continuous simple harmonic motion of sufficient frequency to affect the organ of hearing. Such vibrations are regular; they recur in equal intervals of time,—that is, they are periodic, and they have sufficient frequency to bring the sound within the limits of hearing. This is true not only of the parts of the vibrating body which is the source of the musical sound, but also of the particles of the medium through which the waves are transmitted.

Waves of this character produce a pleasing sensation, and certain combinations of such waves combined with the movement called rhythm are the source of all the pleasure which is derived from music.

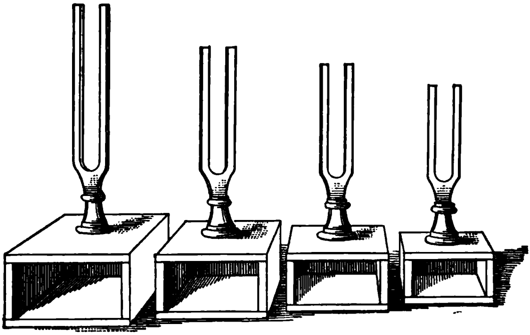
In case of a noise, the vibrations are not continuous. They change abruptly. They consist of different vibrations which do not agree with each other. The sound made by the stroke of a hammer, a wagon rolling over a stony street, an explosion of powder, and so on, are examples of noises.

229. Simple and Complex Tones.

A simple tone is one which is produced by a single kind of vibration, while a complex tone is composed of several different kinds of vibration which are together heard as one.

A good tuning-fork gives forth a nearly simple, or pure, tone. If several forks of the proper pitch are sounded at the same time, a complex tone will be heard, but it will be heard as a single tone, although there are as many different kinds of vibrations as there are different kinds of forks.

FIG. 159.



Complex tone.

The tone which is produced by the largest fork, or, in general, the tone which has the lowest pitch, is called the *fundamental*. The other parts of a complex tone are called *overtones*.

Simple tones are seldom used in music. Several overtones must be combined with a single one to produce a tone of pleasing character. This subject is further discussed in a later section.

229a. How Musical Sounds differ.

There are four characteristic properties of musical sounds. They are *loudness*, *pitch*, *quality*, and *time*. It is by these that one musical sound may be distinguished from another.

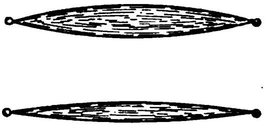
230. Loudness.—Intensity.

Loudness refers to the sensation produced by the vibrations, while intensity refers rather to the energy of the vibrating particles. When the vibrations are intense,—that is, when the medium is greatly strained by the condensations and rarefactions,—there will be a sensation of loudness.

Loudness depends, first, upon the *amplitude of the vibrating body*.

The greater the distance through which a body is made to vibrate, the greater the disturbance and strain of the air which surrounds it. If a stretched wire is gently plucked, it will have only a small amplitude of vibration and will produce only a faint sound. If its amplitude of vibration is increased it will give a louder sound. The keys of a piano are struck gently or with considerable force to secure the desired amplitude of vibration of the piano wires.

FIG. 160.



Difference in amplitude.

Second, *the energy of the vibrating particles of a medium varies inversely as the square of the distance from the body which is the source of the vibrations.* When the distance, for example, is three times as great, the intensity is one-ninth as great. This follows from the fact that waves of sound in a uniform medium move out in all directions. The body of air affected by the waves is then spherical in shape. The surface of a sphere varies as the square of the radius. As the waves advance they cover the surface which is increasing as the square of the distance, and so the intensity decreases as the area increases.

While it is not possible to measure a sensation, yet loudness may be considered as affected in the same manner as the intensity of the vibration which causes the loudness. Loudness decreases as the distance increases, but it is not possible to state any exact rate of change.

Third, *loudness depends also upon the density of the medium.* A sound in hydrogen gas is very weak as compared to the sound originating in the same source in a medium of air at sea-level. Aëronauts in the rare air of the higher regions are obliged to make a special effort in conversing with each other. The air in a diving-bell far beneath the surface of water, is greatly compressed and so is very dense. The divers within speak in subdued tones, that the sound may not be unduly loud.

231. Speaking Tubes.

If sound waves, instead of being allowed to go out in every direction, are conducted mainly in one direction, the energy of the wave would not be so soon dissipated, and ordinary conversation could be carried on at much greater distance. This condition is supplied by the use of tubes, which are frequently used to connect the various parts of large buildings. The voice of a person speaking or whispering at one end of a long tube may be distinctly heard at the other end.

232. Pitch.

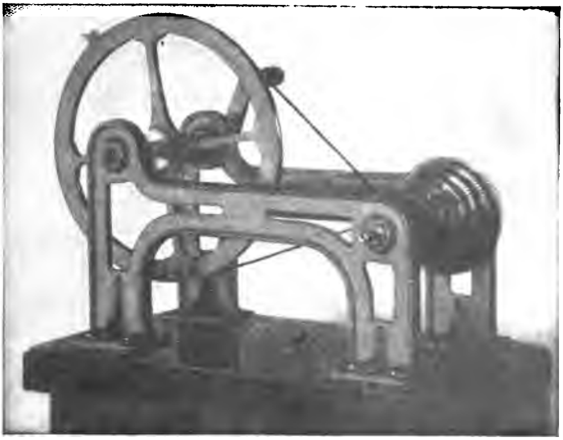
Pitch is one of the chief characteristics of a musical note. It depends on the number of vibrations per second. The greater the frequency of the vibration, the higher will be the pitch.

Experiment 48.

Rotate a toothed wheel, or several of them, as shown in Fig. 161. Hold the edge of a piece of stiff paper to the teeth. A tone of a certain pitch will be heard. Rotate the wheel more rapidly and the pitch will be raised.

Each time a tooth passes the paper, a sound wave is produced. The faster the wheel rotates, the greater the number of waves in a given time. This shows that pitch depends on the number of vibrations in a given time.

FIG. 161.



Toothed wheels.

If several of the wheels are used, all attached to the same axis, the highest pitch will be produced by the one which has the greatest number of teeth.

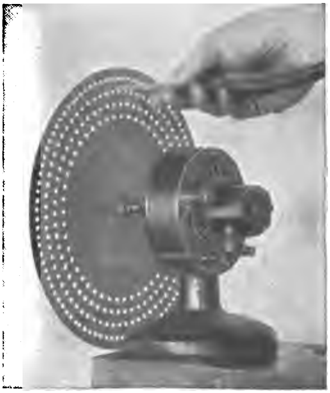
Experiment 49.

A simple form of the *siren* is represented in Fig. 162. It consists of a metal disk perforated with two or more circular rows of holes, as shown.

The disk should be mounted upon a turning table or an electric motor so that it may be rotated at any speed desired.

Hold the end of a tube near the row of holes and blow air through it from the mouth or a bellows. The holes and the spaces between them will pro-

FIG. 162.



A siren.

duce alternate condensations and rarefactions of the air on the other side of the disk. This will produce a musical tone whose pitch will rise when the disk is more rapidly rotated. Thus, again, the pitch is observed to depend on the number of waves per second.

Sound waves of different frequency will travel with the same velocity, and, so, sounds of different pitch will pass through the air and reach the ear in the same time. When the waves are short, there will be more of them in any given distance. The distance a sound travels in one second is always equal to the wave-length multiplied by the number of waves. This may be expressed by the equation

$$V = ln$$

where V is the velocity, l the wave-length, and n the number of waves per second. For example, if sound travels 1152 feet a second and the frequency of the vibration is 256 per second, then the length of each wave would be 4½ feet. If the frequency were twice as great, each wave would be 2¼ feet, and yet the velocity would remain as before.

233. Limits of Perception of Sound.

The ear is so constructed that it responds only to sounds which are within a certain range of vibration frequency. The pitch may be so high or so low that the sound cannot be heard. The frequency of vibration of the lowest audible tone is about 20 per second and of the highest about 40,000 per second. Ears differ in this respect.

The frequency employed in music ranges between 40 and 4000 vibrations per second, other frequencies having little musical value.

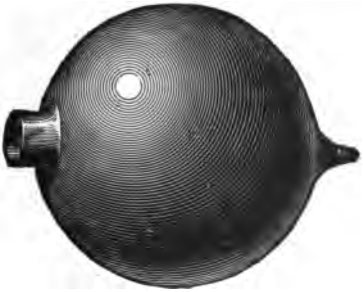
234. Quality.

Two tones may be of the same loudness and the same pitch and yet be distinguished from each other by their *quality*, or *timbre*. A tone from a piano and one from a violin do not sound alike although the pitch and intensity may be the same.

As has already been explained (§ 229), nearly all musical tones are complex, that is, there are several overtones in combination with the fundamental. The fundamental is most prominent, but the practiced ear may also hear several overtones when a tone such as the middle C on a piano is sounded.

Complex tones may be analyzed by use of resonance tubes like the one shown in Fig. 163. If the small end of a tube of this kind be placed in the ear, a loud sound will be heard only when there are waves of a certain frequency. A number of such tubes of various sizes are made, each responding only to a particular vibration frequency or pitch.

Fig. 163.



A resonator.

If, now, a complex tone is sounded and these tubes are successively placed to the ear, any overtones that are present may easily be picked out, each tube being marked with the vibration frequency to which it alone will respond.

If, then, the fundamental and the overtones which have been found, are all sounded together by use, say, of tuning forks of the proper pitch, an exact reproduction of the original complex tone will be heard. Thus complex tones may be analyzed and recombined.

Experiments such as these plainly show that quality or timbre depends on the number and character of the overtones which combine with the fundamental.

It is found that the relative phase (§ 223) and intensity of the overtones also affects the quality of a musical sound, so that we may say finally, that *the quality of a musical tone depends upon the number, the relative phase, and the relative intensity of the overtones which are combined with the fundamental.*

235. The Diatonic Scale.

The ear recognizes a definite succession of musical tones known as the *diatonic scale* or *gamut*. The scale consists of eight notes called the *octave*. The lowest is the *key-note*, or *tonic*. The other notes rise in pitch by well-defined increases in the vibration frequency, as shown in the table below.

A note of any pitch may be selected as the key-note and the scale may then be built upon it by a proper increase in the vibration frequency.

The notes of the scale are indicated by letters of the alphabet and also by names, as follows:

C		D		E		F		G		A		B		C′
do		re		mi		fa		sol		la		si		do
1		$\frac{9}{8}$		$\frac{5}{4}$		$\frac{4}{3}$		$\frac{3}{2}$		$\frac{5}{3}$		$\frac{15}{8}$		2
	$\frac{9}{8}$		$\frac{10}{9}$		$\frac{16}{15}$		$\frac{9}{8}$		$\frac{10}{9}$		$\frac{9}{8}$		$\frac{16}{15}$	

The first row of fractions shows the fractional parts which must be taken of the number of vibrations in the key-note to determine the number for any note in the scale. Thus, if the number of vibrations for the key-note is 256, the proper number for E is $256 \times \frac{5}{4} = 320$; for B, $256 \times \frac{15}{8} = 480$.

This list of fractions should be committed to memory, for they are used in any octave within the range of music.

The letters used in the table above indicate the octave at about the middle of the range of musical sounds. The higher octaves are often marked C', C'', C''' and so on, while lower octaves may be marked C_1, C_2, C_3 and so on. Thus, F'' would be F in the second octave above middle C, and G_3 would mean G in the third octave below.

The number of vibrations for any note is twice as great as for the same note in the octave below, and one-half as great as for the same note in the octave above. To find the number of vibrations for E'' when C is 256, we first calculate that C' is 512 and C'' is 1024, then E in this octave is $1024 \times \frac{5}{4} = 1280$.

236. Intervals.

The fractions in the second row in the table above indicate the *intervals* between the successive notes of the scale.

An interval is the ratio of the frequency of vibration of one note to that of another. Thus the interval from *D* to *E* is $\frac{5}{4} \div \frac{9}{8} = \frac{10}{9}$; *E* to *F*, $\frac{4}{3} \div \frac{5}{4} = \frac{16}{15}$, and so on.

It will be observed that there are but three different kinds of intervals in the scale—$\frac{9}{8}$, $\frac{10}{9}$, and $\frac{16}{15}$.

The interval $\frac{9}{8}$ is called a *major tone*; $\frac{10}{9}$, a *minor tone*; and $\frac{16}{15}$, a *major semitone*.

When two notes are sounded together, the combination is most pleasing to the ear when the interval is expressed by small numbers. Such notes are said to be *consonant*. The intervals of greatest consonance are as follows:

$\frac{2}{1}$, octave, *C* to *C'*.
$\frac{3}{2}$, fifth, *C* to *G*.
$\frac{4}{3}$, fourth, *C* to *F*.
$\frac{5}{3}$, major-sixth, *C* to *A*.
$\frac{5}{4}$, major-third, *C* to *E*.
$\frac{6}{5}$, minor-third, *E* to *G*.

If a note be raised by $\frac{25}{24}$, that is $\frac{10}{9} \div \frac{16}{15}$, it is said to be *sharpened*. The frequency for *G* sharp (G#), for example, is $384 \times \frac{25}{24} = 400$. If a note be lowered by $\frac{24}{25}$, that is, $\frac{16}{15} \div \frac{10}{9}$, it is said to be flattened. The frequency for *E* flat (E♭), for example, is $\frac{24}{25} \times 320 = 307.2$.

237. Standard Pitch.

There is no uniform standard of pitch among the various nations and classes of people. The French standard is *A* =

435. The German standard for the same note is 400. Piano makers in United States use $A = 435$. The so-called concert pitch is $A = 460$. The standard usually employed in physics, known as the physicist's pitch, is $C = 256$.

With 256 as the vibration frequency of the key-note, the number of vibrations for each note in the scale is as follows:

C	D	E	F	G	A	B	C
256	288	320	341.3	384	426.7	480	512

238. The Tempered Scale.

It is often necessary in music to use scales having different key-notes. For example, it may be desired to use a scale in the key of E, G, or some other note. When this is done it is found that the notes of one scale do not fit those of another. If G is selected as the key-note, the interval between G and A is $\frac{10}{9}$, whereas the first interval in the scale should be $\frac{9}{8}$. In case this new scale is given by the voice, a violin, or any instrument whereby the pitch may be readily adjusted, the proper change in the interval may be made; but in pianos and organs the pitch of each note is fixed and the intervals can not be changed at will. If enough of new notes were introduced into the gamut to make the use of the various keys possible, the keyboard of a piano or organ would be unmanageable.

To obviate this difficulty it has been found necessary to change the intervals of the diatonic scale. This change is called *tempering*. The method usually adopted is that of *equal temperament*. By this method there are twelve notes in an octave, each interval being the $\sqrt[12]{2}$ or 1.059. The number of vibrations for any note in the equally tempered scale is found by multiplying the number for the preceding note by $\sqrt[12]{2}$.

239. Beats.

If two notes when sounded together produce a pleasing sensation, the effect is called a *concord*. If the effect is displeasing it is called *discord*.

We have already given (§ 236) a number of combinations which produce pleasing sensations. Numerous other combinations will produce discords.

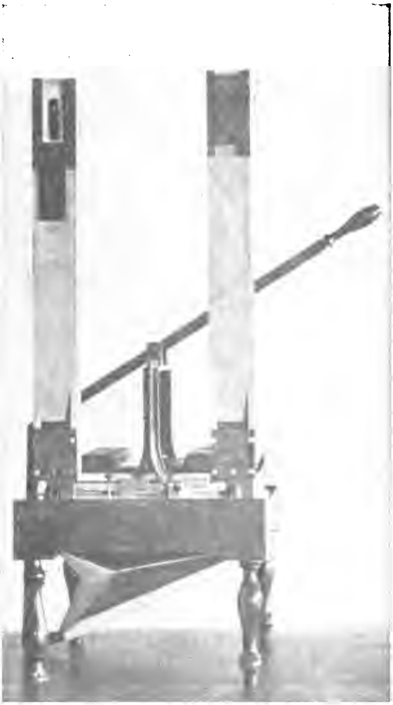
Experiment 50.

(1) Strike a white key and a black one adjacent to it in the lower part of the keyboard of a piano. Press the loud pedal so that the vibrations will continue for some time. The sound has an unpleasant effect, that is, it is discordant. As the sound dies away a distinct succession of *beats* is heard. These produce a kind of throbbing sound wherein loud and soft sounds rapidly succeed each other.

(2) Select two organ pipes which give the same tone. Lower the slide at the top of one of them, as shown in Fig. 164. The pitch will then be slightly different. When the two pipes are sounded together the discord and succession of *beats* will be heard as before.

(3) Mount upon a box two tuning forks of slightly different pitch. When they are made to vibrate at the same time, the sound will be discordant and the *beats* will be heard as in the experiments above. In case the forks have the same pitch, they may be made slightly different by attaching wax or other matter firmly to the ends of the prongs of one of them.

FIG. 164.

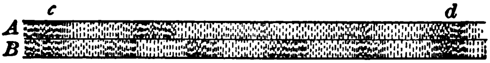


Discord due to beats.

Beats are caused by the interference of sound waves. In Fig. 165, *A* and *B* represent two sound waves composed of condensations and rarefactions. The frequency of vibration in B is a little greater than in A, and hence the waves in B are a little shorter.

If these two wave motions are passing through the air together, it is plain that when two condensations are at the same point, as at c and d, the sound will be loud, but when a condensation and a rarefaction meet, one will neutralize the other and silence will be the result. Thus a succession of soft and loud sounds called beats are produced. The number of beats is always equal to the difference in the frequencies of the two notes. If the frequency for C_2 is 72.5, that for $C\sharp$ is 76.8 in the evenly tempered scale. The number of beats in this case is 4.3 per second.

FIG. 165.



Beats due to difference in wave length.

This interference of sound waves is the cause of discord. When, however, the number of beats is very small or very great, the effect is not unpleasant.

That two sounds may be in concord there must be no audible beats between their fundamentals, their overtones, nor between their fundamentals and overtones.

240. Resonance.

Resonance is the response which one body makes to the vibrations of another.

When two bodies which are capable of vibration have the same frequency, then when one of them is made to vibrate, the other one, if near by, will also vibrate. The vibrations of the second body in this case are said to be *sympathetic*.

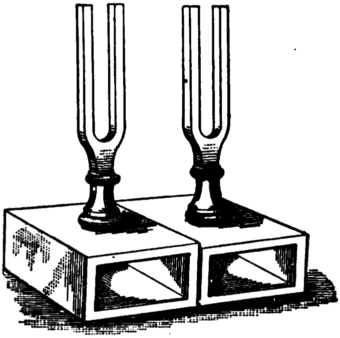
Experiment 51.

(1) Select two tuning-forks which have the same pitch and which are mounted on resonance boxes. Place the boxes side by side and

draw a rosined bow across the ends of one of the forks. After this fork has vibrated for a short time, grasp its prongs with the hand. The same sound, though not so loud, will be heard from the other fork, which is now vibrating in sympathy with the first one.

(2) Open a piano and utter a loud explosive tone near the wires. Utter several tones of different pitch, and in all cases the sound will be reproduced by the piano wires. Since there are numerous wires of different vibration frequency, not only the fundamental but also the overtones of the voice are reproduced by the sympathetic vibrations of the wires.

FIG. 166.



Sympathetic vibrations.

(3) Suspend a heavy ball by a long thread. A puff of air directed against the ball will cause it to swing slightly. A succession of puffs directed against the ball each time it begins to recede from you, will give a greater and greater amplitude to the vibration. The effect of each impulse is added to that of the preceding ones. This, as in the experiments above, is an example of sympathetic vibration.

(4) When a body, having no particular frequency of its own, is set into vibration by another vibrating body, its vibrations are said to be *forced.* A board or box, for example, will vibrate with the frequency of any tuning-fork which may be placed upon them.

241. Resonant Air Columns.

A column of air of a definite length will greatly re-enforce the sound of a vibrating body of the proper frequency. The proper length of air column for a given frequency may be found by raising or lowering a tube, Fig. 167A, in a vessel of water while the vibrating body is held above it. A certain exact length of air column will be found, when the sound will become much louder than before.

FIG. 167A.

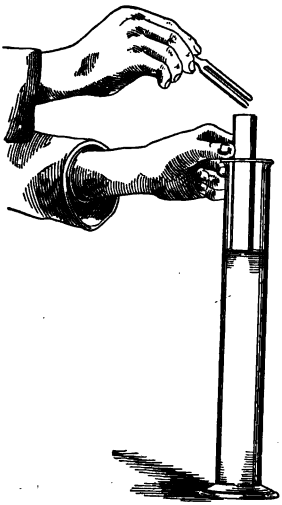
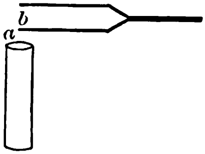


FIG. 167B.



The length of the resonance column.

This phenomenon may be understood by considering the fact that the prong of the vibrating fork, as shown in Fig. 167B, on moving from *b* to *a*, sends a condensation down the tube. This is reflected from the bottom of the air column and returns in time to go with the prong from *a* to *b*. When the prong moves from *a* to *b*, a rarefaction is sent down the air column and returns in time to join the rarefaction above when the prong moves from *b* to *a*. Thus the reflected condensations and rarefactions are in sympathy with the vibrations of the fork and the vibrating body is, in fact, both the fork and column of air.

242. Wave-Length and Air Columns.

The wave length may be determined from the length of a resonant air column. Each sound wave consists of a condensation and a rarefaction, and we have observed that each traverses the length of the column twice during one complete vibration. Consequently the length of the column must be one-fourth of the wave length.

It is found, however, that allowance must be made for the diameter of the tube. If .5 of the diameter be added to the length and this sum be multiplied by 4, the product will be the wave length.

Suppose a column of air 6.13 inches long and one inch in diameter resounds to a tuning-fork whose frequency is 512. Then $6.13 + .5 = 6.63$; $6.63 \times 4 = 26.52$ inches or 2.21 feet. This is the length of one wave under the given conditions.

When the wave length and the frequency of vibration are known the velocity of the sound may be calculated. The length of one wave multiplied by the number of waves per second must be the velocity. Thus, from the data above, $2.21 \times 512 = 1131.52$ feet.

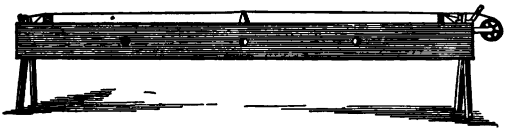
From the velocity the temperature of the air may be roughly determined (§ 226). Thus, $1131.52 - 1090 = 41.52$; $41.52 \div 2 = 20.76°$ C.

243. Vibration of Strings.

The vibration frequency of strings depends on their *length*, *tension*, and *mass*.

The laws according to which the frequency varies may be determined by use of a *sonometer*. This instrument consists of a resonance box about one meter in length upon which, between two bridges, are stretched the wires or strings with which we wish to experiment.

FIG. 168.



A sonometer.

By sliding one of the bridges beneath the wire, it is observed that the shorter the wire is made the higher the pitch will be. When the length is made one-half, the pitch will rise one octave; that is, the vibration frequency is doubled.

(1) *The vibration frequency of a string varies inversely as its length.*

The force with which a string or cord is stretched is called the tension. The wire may be stretched by turning a key around which one end of the wire is fastened, as in a piano or violin. For purpose of experiment it is best to supply the tension by suspending weights from the end of the string. It is found that when the weight is increased four times, the pitch will be raised one octave; that is, the frequency is doubled. If the weight is increased nine times, the frequency is three times as great.

(2) *The vibration frequency varies directly as the square root of the tension.*

Any change in the mass of a string changes the vibration frequency. The greater the mass, the greater the inertia and, consequently, the slower the movement.

(3) *In strings of the same length and tension, the vibration frequency varies inversely as the square root of their masses.*

244. Quality of Music from Stringed Instruments.

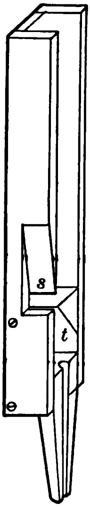
As has already been explained (§ 234), the quality of a tone depends on the character of the combination of overtones with the fundamental. Strings, as a rule, vibrate not only as a whole but also in segments at the same time. These segments produce the overtones which give character to the note. The kind of overtones produced by a string depends largely upon the place and nature of the stroke which causes the vibration. In case of piano wires, it is found that the best quality of tone is secured by having the hammer strike at a point about one-seventh of the distance from the end of the wire.

The volume of sound in all stringed instruments is obtained by attaching the strings to some resonant body. The sound of the piano comes, for the most part, from the "sounding board." The strings of a violin or guitar are stretched upon a resonance box. Not only the loudness but also the quality of the tone is determined by the resonant body. Certain pianos and violins are especially prized because of the quality which has been obtained in this manner.

245. Application of the Laws of Strings.

The construction and operation of many musical instruments are in accordance with the laws of strings as given above. In a piano the wires differ in length and mass, while the tuning is accomplished by change of tension. The same applies to a harp. In a violin the strings differ in tension and size, and the operation of playing consists largely in fixing the proper length by pressure of the strings at various points along the neck of the instrument. The same applies to the guitar and other instruments of this kind.

FIG. 169.



Organ pipe.

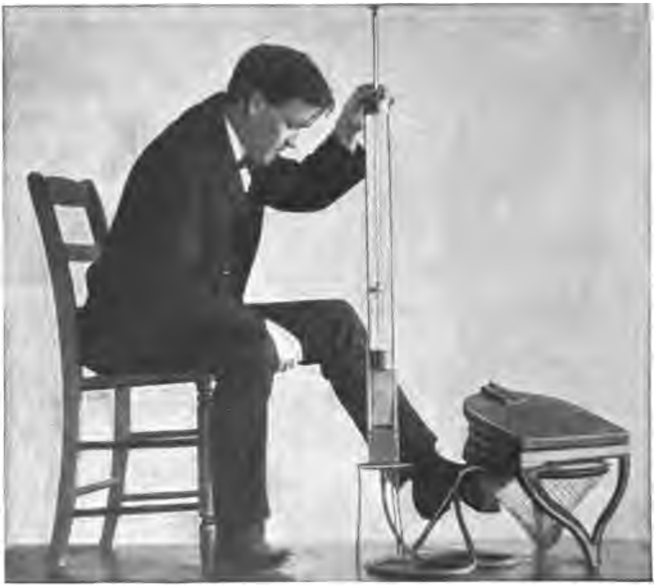
246. Organ Pipes.

Organ pipes are made of wood or metal. A cross section of the pipe may be either square or circular. Near the lower end of the pipe, on one side, is an opening called the *mouth* (Fig. 169). The upper *lip* of the mouth, *s*, ends in a thin edge. Below the mouth is the *throat*, *t*. Air driven into the throat issues in a thin blade against the sharp lip and sets the whole column of air in the pipe into vibration.

247. Nodes and Segments in Organ Pipes.

If a pipe having glass walls is provided, the vibratory movement of the particles of air may be made apparent. A light frame covered with a thin membrane upon which is sprinkled a little fine sand may be lowered by a thread into the vibrating column of air. At certain points the sand will be made to dance up and down. These points are the *segments* where the particles of air move up and down through a short distance as the condensations and rarefactions pass through the column.

FIG. 170.



Locating the nodes and segments in an organ pipe.

At other points the sand will quietly rest on the membrane. These points are the *nodes*, where the air is alternately condensed and rarefied but is not moved along the column.

The longer a pipe is, the greater will be the distance between the nodes and, consequently, the greater the wave length.

The vibration frequency in organ pipes varies inversely as the length of the pipe.

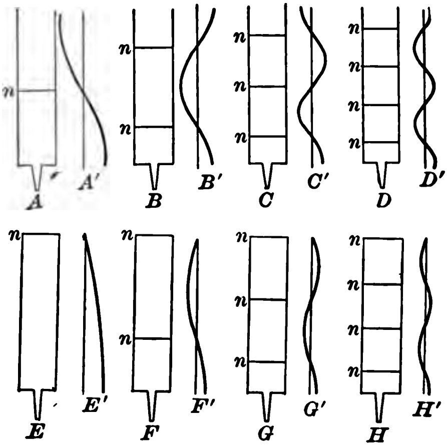
248. Open and Closed Pipes.

All organ pipes are open at the mouth. The other end may be open or closed.

An open pipe will give a note one octave higher than a closed pipe of the same length.

In all pipes there is a vibrating segment at the mouth. In open pipes there is a segment at both ends. In closed pipes there is a node at the closed end. In the diagram, Fig. 171, *A*, *B*, *C*, and *D* are open pipes and the others are closed. The nodes are marked *n*. The spaces between the nodes are the vibrating segments.

Fig. 171.



Organ pipes.

For the fundamental note of the open pipe there is but one node and it is at the middle of the pipe. If the wave be represented by the curved line *A'*, it is seen that the pipe is ½ the wave length of the fundamental note (§ 223). For the first overtone there are two nodes, *B*, *n*, *n*, and the pipe is $\frac{2}{2}$ the wave length. In the third overtone, the pipe is $\frac{3}{2}$ the wave length. In the fourth, $\frac{4}{2}$ and so on.

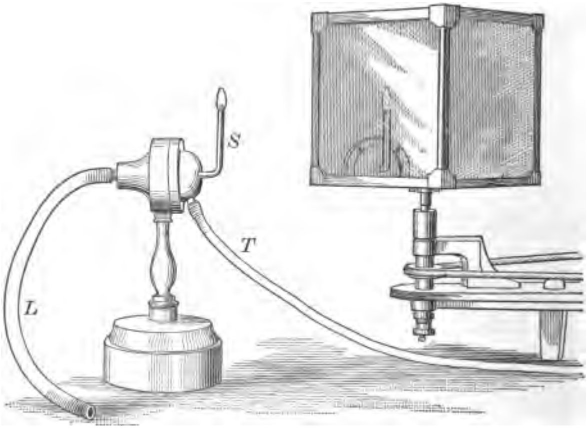
An open pipe has a complete series of overtones.

In closed pipes there is a node only at the closed end when the fundamental is produced. The curved line, *F'*, shows that the pipe is then ¼ of the wave length. In the first overtone there are two nodes and the pipe is $\frac{3}{4}$ of a wave length. In the second overtone, $\frac{5}{4}$. In the third, $\frac{7}{4}$, and so on. Thus the ratio of the frequency of the fundamental to that of the overtones in closed pipes are 1, 3, 5, 7, while in open pipes they are 1, 2, 3, 4.

249. Manometric Flame.

A good experimental proof of the fact that sound waves consist of alternate condensations and rarefactions may be given by use of the apparatus shown in Fig. 172. The cylinder is divided into two equal apartments by a thin membrane stretched across the middle. Illuminating gas is admitted through the tube *T* and comes out through a pointed tube *S*, where it burns as a small flame. The other compartment contains air, and is entered by a tube *L* through which any desired sound wave may be admitted. The flame will burn steadily as long as the membrane is not disturbed, but when the air in the air chamber is set in vibration by a note sung at the end of the tube *L*, the condensation will push the membrane toward the gas, causing

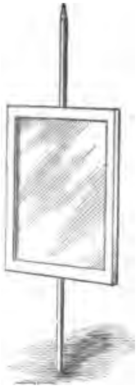
Fig. 172.



Manometric flame apparatus.

more gas to pass through the tube *S*, and the flame then burns higher. A rarefaction will permit the membrane to bend toward the air chamber and, as a result, the flame will be lower. Each wave will alternately raise and lower the flame.

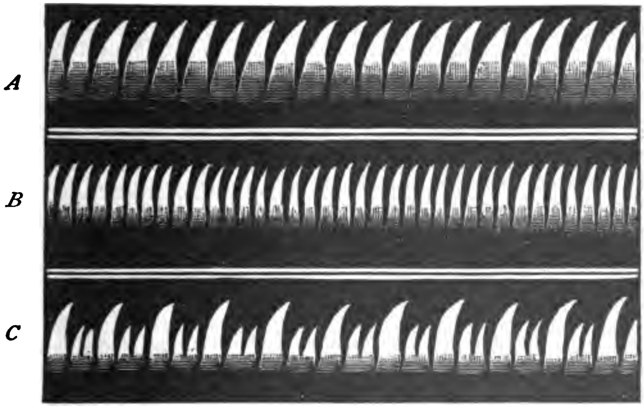
FIG. 173.



The rise and fall of the flame is so rapid that the movement cannot well be directly observed; but when a mirror is rotated near by, the flame as seen by reflection will rapidly change its position and thus the high and low parts are separated. The mirror should be double, that is, composed of two mirrors placed back to back and mounted in a frame as shown in Fig. 173, or cubical as in Fig. 172.

The flame thus observed appears as a toothed band and is called a *manometric flame*. For a certain tone sung into the air chamber of the apparatus the band may have the appearance shown in Fig. 174, *A*. As the pitch of the note is

FIG. 174.



Manometric flames.

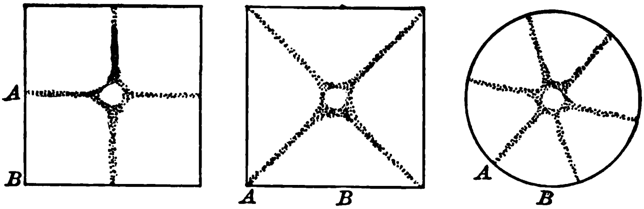
raised, the number of teeth will increase. When the pitch is one octave higher, the number of teeth will be doubled, as at *B*.

The overtones also appear as teeth upon teeth, as at *C*.

250. Vibration of Plates.

When plates of glass or metal are clamped at the center and sand is sprinkled over them, the nature of their vibration may be observed by the action of the sand. In Fig. 175 the arrangement of the sand is shown in several cases when the finger is touched to the plate at the points *A* while a rosined bow is drawn across the edge of the plate at the point *B*. The sound is thrown off the vibrating sections into the nodes which are not vibrating. The smaller the vibrating segment, the higher the pitch.

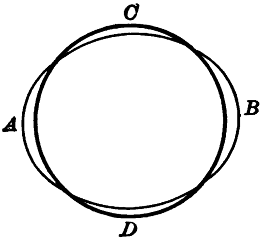
FIG. 175.



Sand figures produced by vibrating plates.

A vibrating bell may divide into four segments, as shown in Fig. 176. When the quarters *A* and *B* are moving outward, *C* and *D* are moving inward, and *vice versa.*

FIG. 176.



Vibrating bell.

Problems.

1. When the frequency of vibration is 82 per second and the velocity of the sound is 333.8 m., what is the wave length?

Ans. 407.07 cm.

2. How many condensations would there be in a space of 50 feet of air at 0° C. when the frequency of the source of the vibration is 545? *Ans.* 25.

3. If the siren disk be rotated 900 times a minute, what will be the frequency of vibration from the row of 16 holes? *Ans.* 240.

4. How long a time will be required for sound to travel through air at a temperature of 22.5° C. a distance of 1 mile? *Ans.* 4.65 sec.

5. What is the error of a watch which is set by the stroke of a town clock at a distance of 3.2 kilometers when the air is at freezing temperature? *Ans.* 9.6 sec. slow.

6. If air has a temperature of 16° C. and water is at its maximum density, how much sooner will a sound wave reach the opposite side of a lake through the water than through the air, the lake being 2800 meters wide? *Ans.* 6.2 sec.

7. How far distant must a reflecting surface be that the echo may not return for 1.5 seconds when the air is at a temperature of 24° C.? *Ans.* 853.5 feet.

8 Compare the intensity of vibration of a sound wave at a distance of 3 cm. with that at a distance of 12 m. *Ans.* 16 : 1.

9. If the frequency of vibration is 259 and the wave length is 1.3 m., what is the temperature of the air? *Ans.* 7.83° C.

10. If the key-note requires 289 vibrations, how many vibrations will produce *E* on the diatonic scale? *Ans.* 361.25.

11. How many vibrations are required for F'' when the key-note has physicist's pitch, on diatonic scale? *Ans.* 1365.3.

12. What is the vibration frequency for D_1 on the diatonic scale, concert pitch? *Ans.* 155.25.

13. When the key-note is 256, what is the requisite number of vibrations in the diatonic scale for G♭? *Ans.* 368.6

14. When *C* is 256, what is *D* in the tempered scale? *Ans.* 287.1.

15. When an air column 12.5 inches long and 1 inch in diameter resounds to a tuning-fork making 256 vibrations per second, what is the velocity of sound? *Ans.* 1109.3 feet.

16. Two strings are of the same size and material. The first is twice as long as the second, and the tension of the second is four times as great as that of the first, what is the ratio of their frequencies? *Ans.* 1 : 4.

17. How long must an open organ pipe be that its first overtone may have the same frequency as that of the fundamental of another pipe of the same kind 4 feet long? *Ans.* 8 feet.

CHAPTER XIII.

LIGHT

251. Definition.

Light, like sound, may be defined in two ways.

(1) *Light is a sensation received through the organ of sight and caused by waves which are transmitted on the ether.*

(2) *Light is a rapid vibratory motion which is transmitted in the form of waves on the ether.*

We have seen that sound waves consist of condensations and rarefactions in which the particles of air move back and forth in short periodic excursions. Light waves, however, consist of rapid periodic changes in the condition of the ether (§ 18) and not in an actual motion of the ether itself.

252. Light and Heat.

In nearly all cases, those bodies which give out light are also very hot. The light waves and the heat waves are the same in character but different in length. The light waves are shorter. The heat waves are not visible because the eye is so constructed that only waves of a certain length will produce the sensation which we call vision. Whether the waves are long or short, they are transmitted at the same speed on the ether, but in proportion as they are shorter the greater will be the number which will fall upon the retina of the eye per second. When the proper number of waves per second has been reached, light is produced and will continue until the number is about twice as great, when the light will again cease (§ 302).

We have seen that the ear is limited in the perception of sound to a certain range in pitch. The eye is also limited in its perception of light to a much shorter range of changes in the wave length.

When a platinum wire is heated, it first radiates heat waves (§ 193), but they cannot be observed for reasons just given. If the heating is continued, there will be observed a dull glow which will become whiter and whiter as the number of waves per second increases.

253. Luminous Bodies.

Luminous bodies are those which give out light to other bodies. For example, the sun, the arc of an arc-lamp, a candle flame, or a star.

Non-luminous bodies are those which are not the origin of light waves but may become visible when the waves from luminous bodies fall upon them and are reflected thence to the eye. For example, the moon, the planets, a tree, or a building.

Certain substances such as chlorophyll, solutions of quinine, and others, are *fluorescent*, that is, they become luminous while other light is falling upon them but cease to be luminous as soon as the light is withdrawn. The barium platino-cyanide which is used on the screens of fluoroscopes for the detection of x-rays, has this property.

Other substances, such as calcium sulphide, possess the property of *phosphorescence*, that is, if light be allowed to fall upon them for a time and then removed, they will continue to be luminous. The luminous paint sometimes used on match-boxes, door-plates, and elsewhere, contains material having this property.

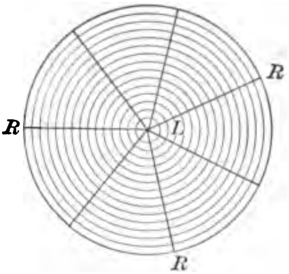
254. The Path of Light.

The light waves move out in every direction from a luminous point. The portion of the ether which is affected by the waves is spherical in shape provided there are no obstacles in the way.

A *ray* is simply the direction in which the wave of light is advancing, as *LR* in Fig. 177. A number of parallel rays are together called a *beam*. A number of rays converging to a point are together called a *pencil*.

When rays of light separate farther and farther from each other as they advance, they are said to be *divergent.* When they come closer and closer to each other, they are said to be *convergent.*

FIG. 177.



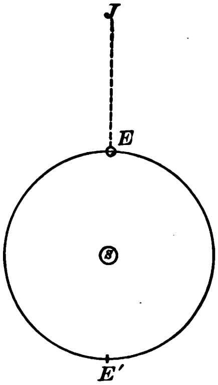
Rays of light.

Waves of light, like all waves, move in straight lines when the medium through which they pass is the same in all directions. An object is seen by the waves of light which come from it to the eye. When these waves travel in a straight line the object is seen in its true place. It is presumed, in sighting along a gun, that light moves in a straight line, otherwise the sighting would be of no advantage.

255. The Speed of Light.

The speed of light is about 186,000 miles per second. At this rate it would pass around the earth more than seven times a second.

FIG. 178.



Roemer's experiment.

For a long time it was supposed that no time at all was required for light to pass from one point to another. It was not till the latter part of the seventeenth century that an experiment was made showing that light had a finite speed. Roemer, in 1676 A. D., discovered that the eclipse of the moons of Jupiter occurred later and later as the earth receded from that planet, and earlier as the earth approached it. The difference in time, he explained, resulted from the difference in the distance of the earth at the time of observation.

In Fig. 178 let *S* represent the sun, and the circle *EE′* the path of the earth. At one time in the year the earth, *E*, is in conjunction with Jupiter, *J*, and then it will, six months later, be in opposition at *E′*.

As the moons of Jupiter revolve they are eclipsed whenever they pass into the planet's shadow. If the earth and Jupiter would remain the same distance apart, the eclipse would appear to recur in equal intervals of time. Roemer observed the innermost moon, which revolves about the planet every 1¾ days. He observed the eclipse when the earth was at *E* and noted the time. It should recur every 1¾ days, but as the earth moved from *E* to *E′* the eclipse appeared, at successive observations, to recur a little later than the time calculated. When the earth was at *E′*, this difference in time amounted to 16.6 minutes.

The difference in distance from Jupiter to *E* and to *E′* is the diameter of the earth's orbit. Since the distance of the earth from the sun is about 92,500,000 miles, the diameter of the orbit is about 185,000,000 miles. If then it requires 16.6 minutes for light to travel 185,000,000 miles, the speed of light must be about 185,700 miles per second.

More accurate experiments made in recent time by other methods give the speed of light as about 299,850 kilometers, or 186,380 miles, per second.

256. Opaque. Translucent. Transparent.

A body is said to be *opaque* when it will not permit waves of light to pass through it. For example, lead and iron.

A body is *translucent* when light will pass through it but objects from which the light comes are not distinctly visible. For example, ground glass.

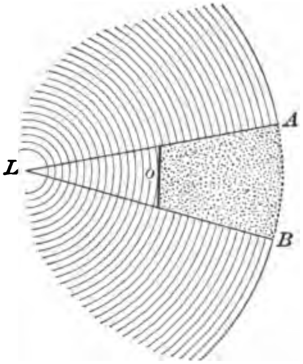
A *transparent* body is one through which light may freely pass and objects may be distinctly seen. For example, glass, quartz, and water.

Most opaque substances in the form of very thin sheets may become translucent or even transparent, and transparent substances of great thickness may become opaque. A very thin shaving of wood or thin paper is not opaque, and very deep water, however clear, is not transparent. Light will penetrate slightly even the most opaque substance and it is to some extent impeded by the most transparent substance.

257. *Shadows.*

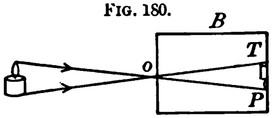
When an opaque body is placed in the path of waves of light, the waves do not appear to bend around the object as sound-waves and water-waves would do. Thus if *L*, Fig. 179, is a point of light and *o* is an opaque object, then the region beyond *o* will receive no light and the lines *LA* and *LB* which separate the light and dark regions are perfectly straight lines. This principle is utilized in the construction of the "pin-hole camera." A box *B*, Fig. 180, has at the center of one end a small hole *o*. A candle flame in front of the hole will form an image of itself upon a screen placed within the box. The rays of light which enter the hole from the point of the candle flame will pass on into the box in a straight line to the point *P*. The rays from the lower end of the candle pass to *T*. Rays from other points of the candle pass to corresponding points of the image. All other rays from the candle are shut out by the box.

FIG. 179.



Shadow.

FIG. 180.



Pin-hole camera.

Experiment 52.

An apparatus for illustration of the above principle may easily be made of a closed box about 10×10×20 cm. In one end cut a hole about

1 inch in diameter. Over this hole fasten a thin piece of tin or brass through the center of which is a hole about as large as a pin-point.

Within the box, about half way between the ends, fasten a partition of ground glass or oiled paper. In the center of the other end of the box cut a hole about 1 cm. in diameter through which to observe the image on the partition. The lid of the box must be tightly closed during observation.

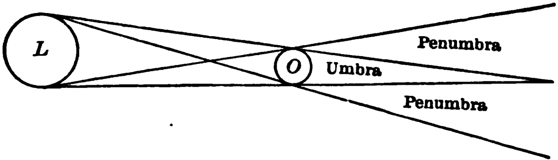
A shadow is the space from which light is excluded by an opaque body.

Shadows are of two kinds, called the *umbra* and the *penumbra*.

When the source of light is a single point, as in Fig. 179, the shadow is an umbra only. But when the luminous body has sensible dimensions as *L*, Fig. 181, then there will be both umbra and penumbra.

When the opaque body is smaller than the luminous one, the umbra will converge to a point (Fig. 181). This is the nature of the shadow cast by the earth, for the sun is larger than the earth.

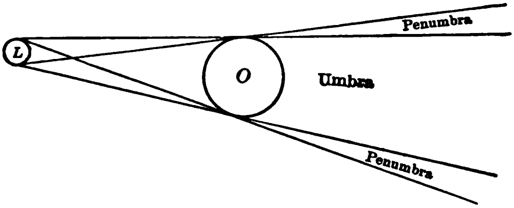
Fig. 181.



Umbra and penumbra.

When the opaque body is the larger, the umbra will be as represented in Fig. 182. This is the kind of shadow usually

Fig. 182.



Shadows when opaque body is larger.

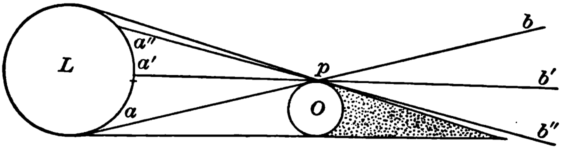
observed, as, for example, when the hand is held in the path of the light from an electric lamp.

The umbra does not abruptly change to penumbra, but gradually shades off through the penumbra to the line where the penumbra ceases.

Experiment 53.

The cause of the penumbra may be clearly explained by making a diagram as shown in Fig. 183 and by holding a ruler *ab* as though it were pivoted at *p*. No obstruction is offered to the light from *L* in the space above *ab*. If the ruler be turned on the pivot *p* to the position *a′b′*, it will mark the line along which only about half the luminous body can shine. The region along *a″b″* will receive light from only a small upper portion of *L*. Thus the shadow grows deeper and deeper until the umbra is reached.

FIG. 183.



Cause of the penumbra.

258. Intensity of Light.

The *intensity* of light is determined by the amount of energy in the light waves. The intensity of sound, as has been shown, is similarly dependent.

The amount of light which falls upon a given unit of area is called the *intensity of illumination.*

Brightness is the name of a sensation, as is loudness in the case of sound. The degree of brightness depends upon the intensity of the light, but the eye is not capable of measuring the intensity with any degree of accuracy. The eye is, however, able to detect very slight differences in the illumination of two surfaces which are side by side.

The intensity of light varies inversely as the square of the distance from its source. This is the law of inverse squares for light. We have had a similar law for intensity of sound.

Suppose it is desired to compare the intensity of light at a distance of 4 m. and 12 m. from the same source. These distances are in the ratio 1 : 3. By the law, the intensities will then be as 9 : 1, that is, $\frac{1}{9}$ as great at the greater distance.

259. Photometry.

Photometry is the process of measuring the illuminating power of the light from any given source.

In any kind of measurement it is necessary first to adopt a standard as a unit. The standard generally employed for light is the *candle power.* The intensity of the light from a sperm candle which is consumed at the rate of 120 grains per hour is termed one candle power (1 c.p.).

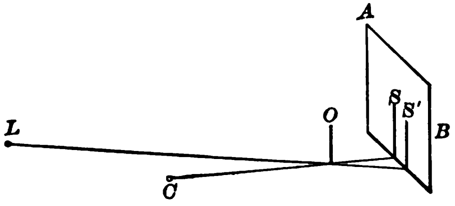
The candle itself is not often used in practice, as various lamps are now made which furnish this unit in a much more reliable and satisfactory manner.

The instrument by which the candle power of a light is determined is called a *photometer.*

260. Rumford Photometer.

The principle of the Rumford photometer is that a screen is equally illuminated by each of two sources of light whenever the two shadows cast by the same object are equally illuminated, that is, have the same depth of shadow. In Fig. 184, *L* and *C* are the two sources of light, *L* being a lamp, say, and *C* a standard candle. An opaque rod is

FIG. 184.



The Rumford photometer.

placed near the white screen *AB*. Two shadows will be formed on the screen side by side.

The light from *C* falls upon the shadow *S′*, and the light from *L* falls upon the shadow *S*.

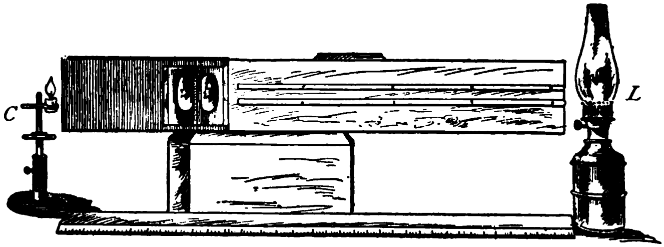
The distances of *L* and *C* from the screen may be adjusted so that the two shadows will look exactly alike.

Since the intensity of any light varies inversely as the square of the distance increases, then the comparative power of two sources of light must vary directly as the squares of their distances from the screen which they illuminate equally. Thus if *C* in the figure is 50 cm. and *L* is 200 cm. from the screen and the shadows are alike, the distances are as 1 : 4. The illuminating powers are then as 1 : 16. If *C* is 1 c.p., then *L* is 16 c.p.

261. Bunsen Photometer.

The use of the Bunsen photometer depends on the fact that a translucent spot in the center of a white screen will have the same appearance as the rest of the screen when the illumination on the two sides are equal.

FIG. 185.



Bunsen photometer.

A spot in a sheet of white paper may be made translucent by means of a little grease or oil. If this sheet be then held between the eye and a window or other source of light, the grease spot will appear brighter than the surrounding paper. On the other side of the paper the spot appears much darker than the paper. In the first case, light is transmitted through the spot to the eye; while in the second case, more light is reflected from the paper to the eye than from the spot. When the illumination is the same on both sides, then the light which the eye receives by transmission through the spot in addition to that reflected from the spot is just equal to that reflected from the white paper. The grease spot will then apparently disappear.

Two mirrors, Fig. 185, may be set at such an angle that the observer can see both sides of the screen at the same time.

The lights *L* and *C* are placed at such distances that the screen has the same appearance on both sides.

The power of the sources of light are then in the same ratio to each other as the squares of their distances from the screen.

Suppose the screen is equally illuminated by *C* at a distance of 60 cm. and *L* at 270 cm. from the screen. Then we can form the proportion

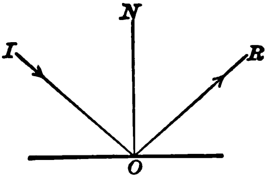
$$C : L = 60^2 : 270^2$$
$$\therefore\ C : L = 1 : 20.25.$$

This means that the illuminating power of *L* is 20.25 times as great as that of *C*. If *C*, then, is 1 c.p., *L* is 20.25 c.p.

262. Reflection.

When waves of light meet an obstacle in their path, they are reflected according to the following law: *The angle of reflection is equal to the angle of incidence.*

FIG. 186.

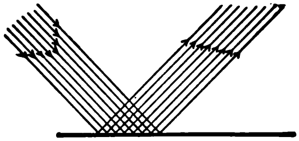


Angles of incidence and reflection.

The ray *IO* is called the incident ray; *OR*, the reflected ray; the angle *ION* is the angle of incidence; *NOR* is the angle of reflection; *NO* is the normal, or perpendicular, to the reflecting surface.

When light is reflected from a smooth surface, such as plane polished metal or glass, the reflected rays continue in the same relation to each other as before reflection (Fig. 187).

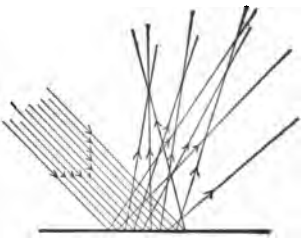
FIG. 187.



Reflection from a polished surface.

If the surface is not polished, as the surface of the paper in this book, the rays are reflected from a countless number of small surfaces which are not in the same plane. Each ray is reflected according to the law given above; but since the small surfaces from which they are reflected are at every possible angle to each other, the reflected rays will be in every possible direction (Fig. 188). Such light is said to be *diffused.*

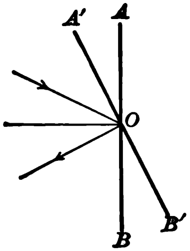
FIG. 188.



Reflection from unpolished surface.

Most objects are seen by diffused light. A perfectly plane, polished reflector can not be seen at all.

FIG. 189.



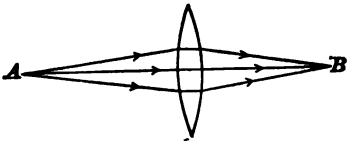
Effect of rotating the mirror.

When a mirror, or other reflecting surface, is turned through a certain angle, say, AOA', Fig. 189, the reflected ray will be turned through twice that angle. This is apparent from a study of the figure. AB is the mirror in the first position and $A'B'$ is its position after it is turned. The normal will be turned as much as the mirror. Since the incident ray is not changed, the angle of incidence will be increased by as great an angle as that through which the mirror is turned. Consequently, that the angles of reflection and incidence may remain equal, the reflected ray must turn through an angle equal to that by which the former angle of incidence was increased and the angle of reflection was decreased, that is, twice the angle through which the mirror was turned.

263. Images.

An image is the appearance of an object at a place where no object exists in fact.

FIG. 190.



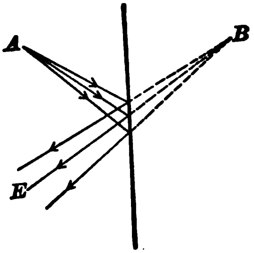
Images.

An image is formed whenever the rays of light coming from a point again meet or seem to meet at a point. Thus in Fig. 190, if rays diverging from *A* pass through a lens and are brought to a point at *B*, an image of *A* will be formed at *B*.

If, however, as shown in Fig. 191, the rays from *A* are reflected from a plane they will not meet at another point, but the eye at *E* will see an image at *B* where the rays would meet if they were extended in that direction.

There are two kinds of images—*real* and *virtual*. The real image is formed when the rays actually meet, as in Fig. 190. The image is virtual when the rays only appear to meet, as in Fig. 191.

FIG. 191.



Virtual image.

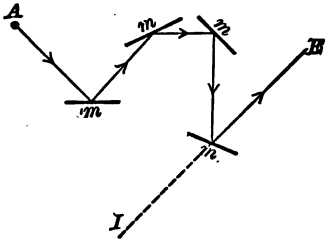
In the formation of images described in this chapter the following facts should be constantly borne in mind:

(1) *An image is always formed at the place where the rays, diverging from a point, come to a point.*

(2) *An object or an image is always seen in a direction along the ray of light as it enters the eye.*

No matter how many times the ray may have been turned from its course in traveling from the object to the eye, the object or image will always be seen in a straight line traced back along the ray just as it entered the eye. In Fig. 192, a ray of light from A is turned out of a straight course four times by reflection from mirrors. It finally enters the eye at E and the image is seen at I in the direction EI.

FIG. 192.



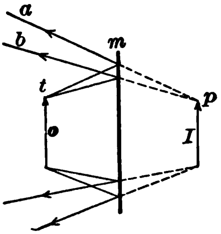
Direction of the image.

264. Images in Plane Mirrors

An image seen in a plane mirror is always virtual. This results from the fact that the rays from a point are diverging before reflection and will continue in the same relation to each other after reflection. Therefore no real image can be formed by a plane mirror.

If, as shown in Fig. 193, an object, o, is placed before the mirror, m, the position of the image, I, may be found by drawing two or more rays to the mirror from each extremity of the object. The rays must be drawn according to the law of reflection (§ 262). The image of the arrow-head is located at a point where the two rays, a and b, would intersect if extended back of the mirror to p. All the rays from the arrow-head that are reflected from the mirror would appear to be coming from p, but two only are needed to locate the point. In the same manner the image of the tail of the arrow may be located.

FIG. 193.

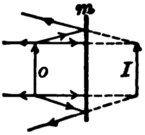


To locate an image in a mirror.

Instead of the two oblique rays from each point, one of them may be perpendicular to the mirror, as shown in Fig. 194. In the latter case both the incident and the reflected ray will coincide with the normal.

It should be clearly understood that there are an infinite number of rays from each point of an object and that all of them after reflection appear to come from a corresponding point of the image. Two rays from points at the end of the arrow, Fig. 193, are all that need to be drawn to find the position of the image, but an infinite number of rays emerge not only from these two points but also from all the points along the arrow. The image of the middle of the arrow may be found by a drawing similar to that employed for one of the ends.

FIG. 194.



Second method.

The image always appears as far back of a plane mirror as the object is in front of it.

This is apparent from the drawing, for the two reflected rays, *a* and *b*, Fig. 193, if traced back to the points where they actually meet (*t*), or seem to meet (*p*), must be traced to the same distance on either side, because the lines have the same angle of divergence.

An easy geometrical proof may also be given. In Fig. 195, let *o* be the object; *ox* and *op* the incident rays; *m*, the mirror; and *n*, a normal to the mirror. These two rays after reflection will appear to come from *i*, hence *i* is the image of *o*. Since *ox* and *np* are both perpendicular to the mirror, $\angle xop = \angle opn = \angle npr = \angle xip$.

FIG. 195.

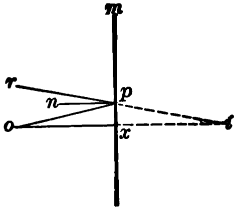


Image distance in a plain mirror.

$$\therefore \angle xop = \angle xip.$$
$$\therefore \triangle xop = \triangle xip,$$

for the corresponding angles of each are equal and they have the side *px* common.

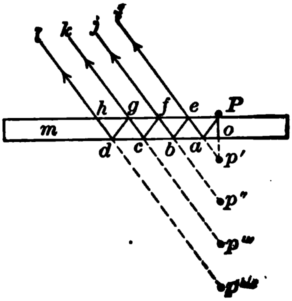
$$\therefore ox = xi,$$

that is, the object and its image are at an equal distance from the mirror.

265. Several Images of One Object in a Plane Mirror.

If an object, such as a pencil, be laid upon a thick mirror, *m*, Fig. 196, and the image be viewed from one side, several images will be seen, each a little dimmer than the one above it. The explanation of this phenomenon may be understood by consulting the diagram. A ray passing from P to o reaches the silvered side of the glass where the reflection in a mirror, for the most part, occurs. This ray is returned to P. A second ray, Pa, say, is reflected to e and on out to i. The first image, then, the distinct one, is at p'. The beam, however, does not wholly emerge from the glass at e. It is, in part, reflected to b, then to f and on out to j. A second image, much dimmer, is thus formed at p'', and the distance from b to p'' is equal to the sum of the distances Pa, ae, and eb. But again a part of the beam is reflected from f to c and then to g and k. Thus a third image, still dimmer, is formed at p''', and so on.

Fig. 196.

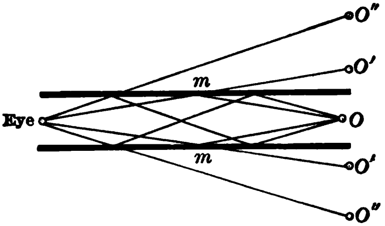


Multiple images.

266. Multiple Images formed by Two Mirrors.

When two plane mirrors are placed parallel and facing each other, several images of the same object may be seen.

Fig. 197.



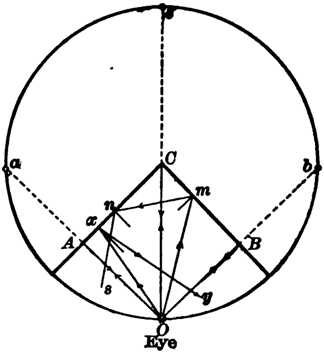
Images in parallel mirrors.

Thus, in Fig. 197, let m and m' be the mirrors; O the object; and let the eye be placed as marked. First there will be the images O' O', formed in the usual manner, one in each mirror. Next, certain rays will be reflected from one mirror to the other and then to the eye, forming images O'' O''. Rays may be reflected a number of times back and forth between the two mirrors before reaching the eye. Thus, an indefinite number of images in a straight line may be formed.

When the two mirrors are placed at right angles, Fig. 198, an object may be seen at four places, three of them being the location of images.

CA and *CB* are the mirrors. *O* is the object. The eye is placed close to the object. The ray from *O* to *B* returns to the eye and the image is seen at *b*. The ray from *O* to *A*, in like manner, returns to the eye, and the image is seen at *a*. The ray from *O* to *C* is returned in the same path to the eye and the image is seen at *c*. In all three cases the image is as far beyond the mirror as the object is in front of it. Consequently, if *C* be taken as a center with a radius *CO*, the circle described will pass through the object and the images.

FIG. 198.



Images in plane mirrors at right angles.

No other images will be formed because no other rays of light from *O* will, after reflection, be returned to the eye. The ray *Ox*, for example, will be reflected to *y*, and *Om* will be reflected to *n* and then to *s*.

In all cases the object may be seen as many times as the number of degrees in the angle formed by the two mirrors is contained in 360. In the case just considered, $360 \div 90 = 4$.

When the mirrors are set at an angle of 60°, the object will appear in six places on the circle. $360 \div 60 = 6$.

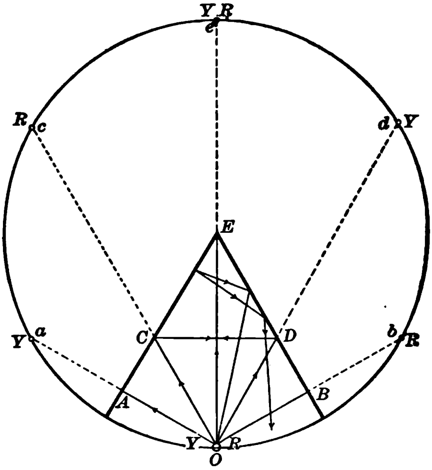
The path of the rays may be traced in Fig. 199.

The object and the eye are at *O*. The object may, for convenience, be a small sphere, red on one side and yellow on the other.

The rays *OA* and *OB* are perpendicular to the mirrors and fix the images *a* and *b*, *a* being yellow, and *b* red.

The ray *OC* is reflected across to *D* and thence back to the eye at *O*. Hence the eye sees a yellow image at *d*. In like manner the ray *OD* is reflected to *C* and thence to *O*, and the eye sees a red image at *c*.

Fig. 199



Mirrors at angle of 60°.

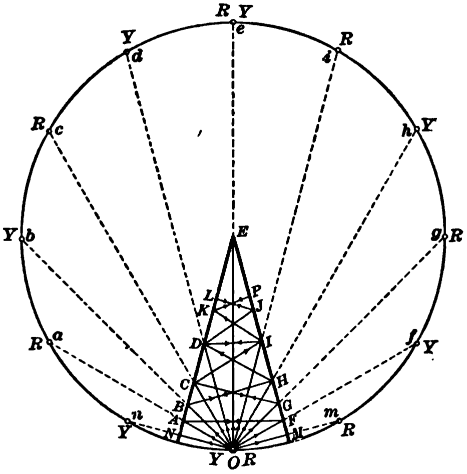
The distance *Cc* is as great as the sum of *OD* and *DC*, and *Dd* is equal to the sum of *OC* and *CD*, because an image is always seen as far back of a plane mirror as the rays traveled from the object to the mirror.

The ray *OE* is returned directly to the eye and so the image will be at *e* and will be yellow on the left and red on the right as viewed from *O*.

If the mirrors be now set at an angle of 30°, the object may be seen in twelve different positions on the circle, 30° apart.

The path of the rays in this case are indicated in Fig. 200. The eye and the object are placed at *O*, *O* being yellow on the left and red on the right.

FIG. 200.



Mirrors at an angle of 30°.

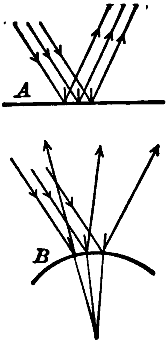
The student is urged to study this figure and trace each ray till it returns to the eye at *O*. For example, the ray *OD* is reflected to *J*, thence to *L*. It is perpendicular to the mirror at *L* and so it will return on the same path to *O*. Hence an image of the yellow side of the object will be seen at *d*.

267. Spherical Mirrors.

If a segment were cut from a hollow sphere and the surfaces were polished or silvered, each side of the segment would be a spherical mirror. The inner side is a *concave* spherical mirror, and the outer side, *convex*.

Such mirrors may be considered as made up of an infinite number of exceedingly small plane mirrors, no two of which are parallel.

FIG. 201.



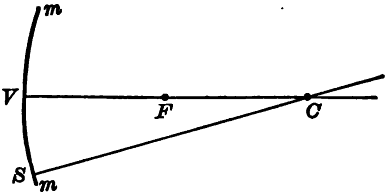
Reflection on plane and curved surfaces.

The law of reflection, that the angle of incidence is equal to the angle of reflection, is as applicable to these curved mirrors as to plane ones, but since the numerous small plane mirrors of which the curved mirror is composed, are not in the same plane, the reflected rays will not have the same relation to each other as the incident rays. Thus, as shown in Fig. 201 *A*, parallel rays reflected from a plane mirror are still parallel, but when reflected, by the same law, from the curved mirror, *B*, are not parallel.

268. Concave Spherical Mirrors.

In the concave mirror, *V*, Fig. 202, is called the *vertex*; *mm* is the *aperture;* the line *CV* is the *principal axis*; *CS* is a *secondary axis*; *C* is the *center of curvature*, that is, it is the center of the sphere of which the mirror may be considered a part; *F* is a point midway between *V* and *C*, called the *principal focus.*

FIG. 202.

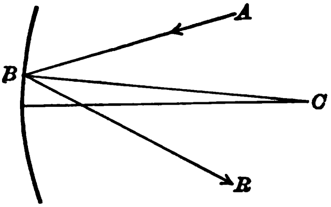


The concave mirror.

Any line drawn from *C* to the mirror will be perpendicular to the mirror at that point. This line then will always be the normal which will be used in making the angle of incidence equal to the angle of reflection. Thus, in Fig.

203, the ray of light *AB* is incident on the concave mirror at *B*. Draw the line *CB*. Then *ABC* is the angle of incidence. On the other side of *CB* construct an equal angle *CBR*. This is the angle of reflection. The ray *AB* is then reflected along the line *BR*.

FIG. 203.

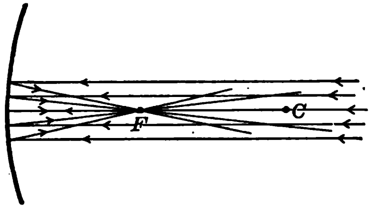


Reflection in a concave mirror.

The principal focus is the point where all the rays parallel to the principal axis meet after reflection.

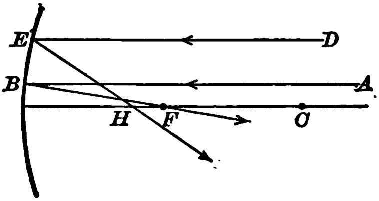
The sun is so far distant that rays of sunlight are practically parallel. When they fall upon a concave mirror they are reflected to the principal focus, forming a point of intense light and heat. (Fig. 204).

FIG. 204.



The principal focus.

FIG. 205.



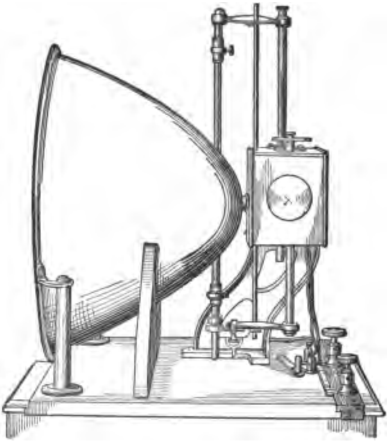
Spherical aberration.

The rays after reflection do not meet at exactly the same point when the mirror is spherical. The ray *AB*, Fig. 205, will be reflected to *F*, but *DE* will be reflected to *H*, a point closer to the mirror. This is called *spherical aberration.*

It is practically true, however, that when the aperture of the mirror is small, the rays parallel to the principal axis will be reflected to the principal focus.

Spherical aberration may be avoided by the use of a *parabolic mirror*, such as is used in search-lights. (Fig. 206).

FIG. 206.



Parabolic mirror used in search-light.

In this case the curve is a parabola and the rays parallel to the axis are all brought exactly to the principal focus. An arc-lamp placed at the principal focus will then send out parallel beams of light.

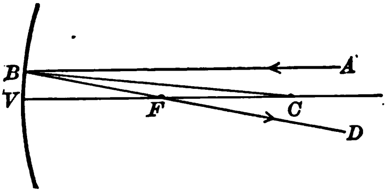
The principal focus is a point half-way between the center of curvature and the vertex of the mirror.

This may be shown from the construction in Fig. 207. *AB* is a ray parallel to the principal axis. *CB* is the normal. *BD* is the reflected ray passing through the principal axis at *F*. By construction,

$\angle ABC = \angle CBD$
but $\angle ABC = \angle BCF$
$\therefore \angle CBD = \angle BCF$
$\therefore \triangle CBF$ is isosceles
$\therefore BF = FC.$

If B is close to V, BF is practically equal to VF. $\therefore VF = FC$ F is therefore midway between V and C.

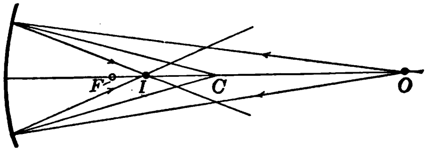
FIG. 207.



Location of principal focus.

If a luminous object is placed at a point O, Fig. 208, the rays of light coming from it to the mirror are divergent. They will then focus at a point, I, a little farther from the mirror than the principal focus. If the luminous object be now placed at I, the rays will pass back over the same paths and will come to a focus at O.

FIG. 208.



Conjugate foci.

When two points are so related that object and image may exchange places, they are called conjugate foci.

O and I, in the figure, are conjugate foci.

Thus it is seen that *a concave mirror will make divergent rays less divergent, parallel, or convergent; parallel rays, convergent; and convergent rays, more convergent.*

269. Images in Concave Mirrors.

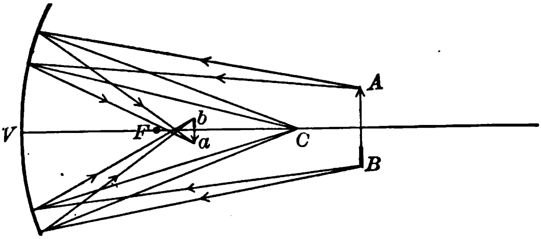
The principles explained above may now be applied in determining the position and nature of images formed by concave mirrors.

We will consider three cases,

1. When the object is beyond *C*.
2. When the object is between *C* and *F*.
3. When the object is between *F* and *V*.

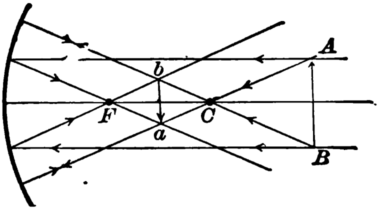
In the Fig. 209 let the object *AB* be placed beyond *C*. Draw lines representing any two rays from each end to the mirror. Next, draw the normals from *C* to each point of incidence. Then draw the reflected rays in accordance with the law of reflection. The two rays from *A* will meet at *a*, and the two from *B* will meet at *b*. The image, then,

FIG. 209.



When the object is beyond *C*.

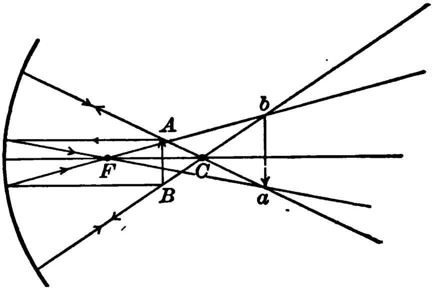
FIG. 210.



A second method.

will be between the two points *a* and *b*. It will be *inverted, real, smaller than the object, and located between F and C.*

FIG. 211.

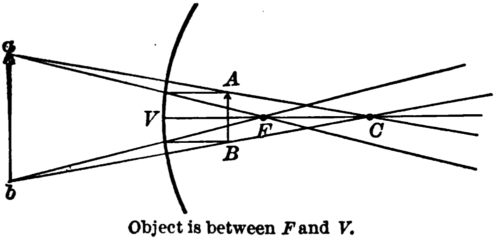


Object is between *F* and *C*

It is possible to make a drawing with the same results, but without constructing angles, as in Fig. 210. One ray from each end is drawn parallel to the principal axis and will be reflected through the principal focus. Another ray from each end is drawn through *C* and hence will return along the same path, for they are normal to the mirror. The image of any point is formed where the rays from that point meet after reflection.

In Fig. 211 the object is placed between *F* and *C*. A drawing similar to that in Fig. 210 shows that the image is beyond *C* and is *real, larger than the object, and inverted.*

FIG. 212.



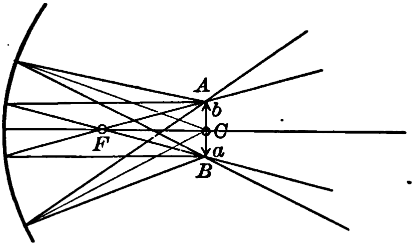
Object is between *F* and *V*.

In Fig. 212, the object is between *F* and *V*. The drawing shows that the rays will still be divergent after reflection, and consequently no real image will be formed, but a virtual image will appear back of the mirror at the points where the rays of light would meet if extended in that direction.

The image in this case is *erect, virtual, larger than the object, and back of the mirror.*

When an object is at the principal focus, there is no image, because the rays after reflection are parallel and so will not meet, however far they may be extended in either direction.

FIG. 213.



The object is at the center of curvature.

When an object is placed at the center of curvature, the rays from it to the mirror are returned along the same lines. Consequently the image is real and has the same location as the object. This, however, is true only of a point at C. If the object has sensible dimensions, as in Fig. 213, the image is *real, inverted, the same in size as the object, and located in the same place.*

270. Images in Convex Mirrors.

The location and character of images in convex mirrors may be found by construction, just as in concave mirrors. Let AB be the object in Fig. 214. Draw two lines, any lines, from A, and two from B, to the convex side of the mirror. Draw lines from C through these points. These lines are the normals. Construct the angles of reflection and extend the rays until they meet.

It is found in this case that the image is *virtual, erect, smaller than the object, and located on the opposite side of the mirror.*

The effect of a convex mirror is to make convergent rays less convergent, parallel, or divergent; parallel rays, divergent, and divergent rays, more divergent.

In general, the concave mirror tends to collect the rays, and the convex mirror tends to scatter them.

FIG. 214.

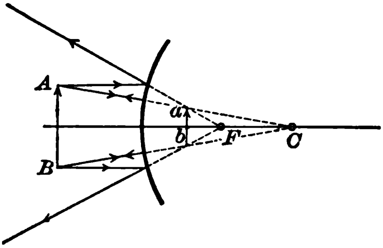
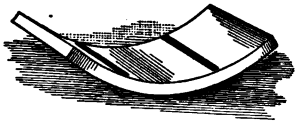


Image in convex mirror.

271. Cylindrical Mirrors.

A cylindrical mirror is a portion of a cylinder. It is curved in one direction and straight in another, as shown in Fig. 215. The general principles for spherical mirrors apply as well to these in the direction of the curve. In the other direction the mirror is plane. The image of the face, as viewed in this mirror, is distorted. This results from the fact that in one direction the image is as it would be in a plane mirror; but in another direction, at right angles to the first, it is as it would be in a spherical mirror.

FIG. 215.



Cyclindrical mirror.

272. Relation of Distances of Object, Image, and Focus.

The relation of the distances of the object, the image, and the focus from the mirror may be concisely stated by the equation,

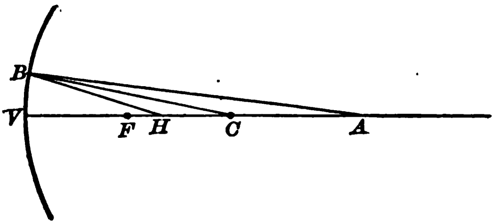
$$\frac{1}{O}+\frac{1}{I}=\frac{1}{F}$$

in which *O* is the object distance, *I* is the image distance, and *F* is the focal distance.

The equation is derived as follows :

A in Fig. 216 is the object. *AB* is the object distance, *O*.

FIG. 216.



Location of O, I and F.

H is the image. *HB* is the image distance, *I*. *FV* is the focal distance. *CV* is the radius, *R*.

BC, by construction, bisects the angle *ABH*. Hence,

$$\begin{aligned} AB : BH &= AC : CH \quad (1) \\ \text{or} \quad O : I &= AC : CH \quad (2) \end{aligned}$$

When *B* is close to *V*, *AB* is practically equal to *AV*; and *HB*, to *HV*. Hence,

$$\begin{aligned} AC &= O - R \\ \text{and} \quad CH &= R - I \end{aligned}$$

Substituting these values in equation (2),

$$O : I = O - R : R - 1 \quad (3)$$

$$\begin{aligned} \text{Hence,} \quad OR - OI &= OI - IR \quad (4) \\ \text{or} \quad IR + OR &= 2OI. \end{aligned}$$

$$\text{Dividing by OIR,} \quad \frac{1}{O} + \frac{1}{I} = \frac{2}{R} \quad (5)$$

Since the focal distance equals half the radius, $\frac{2}{R} = \frac{1}{F}$. Equation (5) then becomes

$$\frac{1}{O} + \frac{1}{I} = \frac{1}{F} \quad (6)$$

Suppose the radius of curvature is 6 cm. and the distance of an object from the mirror is 25 cm., and it is desired to calculate the position of the image. By equation (5),

$$\frac{1}{25} + \frac{1}{I} = \frac{2}{6}$$

$$\therefore I = 3.41 \text{ cm.}$$

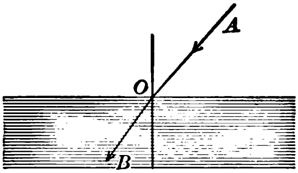
Equation (6) could have been used as well, for if the radius is 6, the focal length is 3.

When the mirror is convex, *I* and *F* when known are considered as negative.

273. Refraction.

Refraction is the bending which occurs when rays of light pass from one medium into another. The ray *AO*, Fig. 217, passes straight through the air to the surface of water, but on entering the water it is bent, so that it passes along *OB*. The ray is refracted at *O*.

FIG. 217.



Refraction.

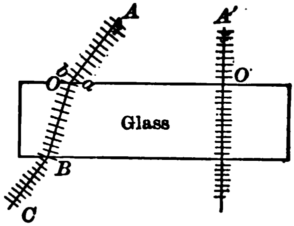
Some media will refract light much more than others. In general it may be said that the more dense a medium is the more the rays will be refracted when they pass into it.

274. Cause of Refraction.

Light moves with less speed through a dense medium than through a rarer one. The speed is less in air than in the ether space beyond the atmosphere. It is less in water or glass than in air.

Let *AO*, Fig. 218, represent a ray of light, that is, the direction in which the waves of light advance. Let the short lines drawn across the ray represent the waves. The wave *ab* is just entering the glass. The end *a* enters first and its speed is checked, while the end *b* continues its speed until it also reaches the glass. Thus the wave is caused to swing about, just as a line of soldiers is swung around when the men at one end of the line do not walk as rapidly as those at the other. The wave will then advance through the glass in a straight line but in a direction OB. At B the wave will again pass into the air. The part which was first to enter at O, is the first to emerge at B. The direction of the wave is again changed and it passes on along BC.

Fig. 218.



Cause of refraction.

In case the ray is perpendicular to the surface of the glass, the speed is checked but there is no refraction, for, as shown in Fig. 218, both ends of the lines on $A'O'$ enter the glass at the same time.

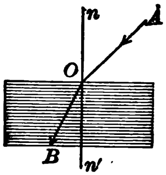
When rays of light pass obliquely from one medium to another of different density, they are refracted. The refracted ray is bent toward the normal when the light passes from a rarer to a denser medium, and from the normal when the light passes from a denser to a rarer medium.

275. Index of Refraction.

The index of refraction is the ratio of the sine of the angle of incidence to the sine of the angle of refraction.

Let AO, Fig. 219, be a ray of light passing from air, say, into water. nn' is the perpendicular, or normal. OB is the refracted ray. Then the angle, AOn, is the *angle of incidence*, and BOn' is the *angle of refraction*.

Fig. 219.



Angles of incidence and refraction.

If, now, a circle of any radius be drawn with its center at o, Fig. 220, the line Ai, perpendicular to the normal, is the *sine* of the angle of incidence, and the line Br is the *sine* of the angle of refraction.

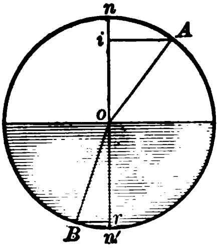
The index of refraction is equal to $\frac{Ai}{Br}$.

If, *Ai* for example, is 4 cm. long, and *Br* is 3 cm., the index of refraction is $\frac{4}{3}$. This is the case when light passes from air into water.

If *Ai* is 3 cm. long and *Br* is 2 cm., the index is $\frac{3}{2}$. This is the case when light passes from air into crown glass.

The index is said to be *absolute* when light passes from vacuum into a substance, and *relative* when the light passes from one substance into another.

FIG. 220



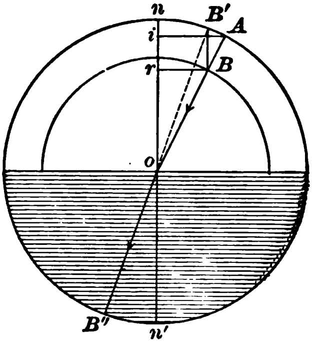
Index of refraction.

When light passes from one substance into another the relative index is found by dividing the absolute index of the second substance by that of the first. Thus if the index for water is $\frac{4}{3}$, and that for glass is $\frac{3}{2}$, then the index for light passing from water to glass is

$$\tfrac{3}{2} \div \tfrac{4}{3} = \tfrac{9}{8}$$

The absolute index for air is very nearly unity, being 1.0003. The index of substances relative to air is, therefore, practically the same as the absolute index.

FIG. 221.



Construction of the refracted ray.

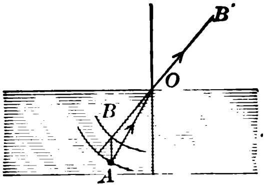
The indices for a few substances relative to air are given below.

Water......	1.33	(about $\frac{4}{3}$).
Rock salt ...	1.55	
Flint glass..	1.66	(about $\frac{8}{5}$).
Crown glass	1.51	(about $\frac{3}{2}$).
Diamond...	2.47	(about $\frac{5}{2}$).
Carbon disulphide.....	1.63.	
Alcohol....	1.36.	

276. Construction of the Refracted Ray.

In Fig. 221, let *Ao* be a ray of light passing through air and entering water at *o*. The index is $\frac{4}{3}$. Draw two circles with centers at *o* and with radii whose length are as 4 : 3. Draw *Ai* and *Br* perpendicular to the normal *nn′* Since. *Ao* : *Bo* = 4 : 3, then *Ai* : *Br* = 4 : 3. Hence if *Ai* is the sine of the angle of incidence, *Br* is the sine of the angle of refraction. If then, *BB′* be drawn parallel to the normal, and a straight ruler be placed on the points *B′* and *o*, the line *oB″*, the refracted ray, may be drawn.

FIG. 222.



From denser to rarer medium.

In passing a ray from water out into air, the same principles hold. In this case the index is $\frac{3}{4}$, for the ray is passing into a rarer medium, that is, the sine of the angle of refraction is the larger. The line *AB*, Fig. 222, parallel to the normal is then drawn from the outer circle to the inner one, and *BO* gives the direction of the refracted ray, *OB′*.

277. Laws of Refraction.

1. *The refracted ray lies in the plane of the incident ray and the normal.*

2. *The index of refraction for a given substance is a constant quantity whatever the angle of incidence may be.*

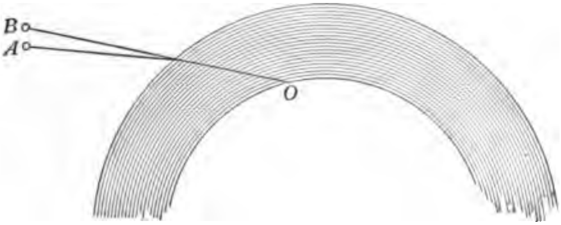
3. *Light is refracted whenever it passes obliquely from one medium to another of different optical density.*

4. *Rays of light are bent toward the normal when they enter a more refractive medium, and from the normal when they enter a less refractive medium.*

278. Common Instances of Refraction.

The light from the sun, moon, planets, and stars can reach us only by passing through the atmosphere. This light is, then, refracted in all cases except when it comes from bodies directly in the zenith. Light which comes from bodies near the horizon is refracted most. As the light passes through the air it is bent downward in a curved line because the air is denser as the earth is approached. Since the direction of rays of light as they enter the eye determines the direction in which an object is seen, an object at *A*, Fig. 223, will be seen at *B*. All heavenly bodies, except those in the zenith are seen in a higher position than that which they occupy in fact.

FIG. 223.

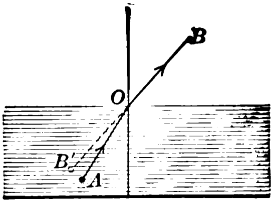


Atmospheric refraction.

An object in water is not seen in its true position. If it is viewed in a direction oblique to the surface of the water, it appears beyond its true position and at a less depth. This is apparent from Fig. 224, where the ray of light starts at *A*, is refracted at *O*, and reaches the eye at *B*. The object is then seen along the line *BO* at *B′*.

Experiment 54.

FIG. 224.

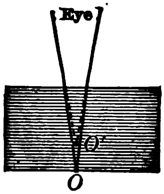


Position of an object in water.

Fill a vessel with water to a depth of about 25 cm. Drop into the water any small object that will sink. Rest a long straight rod or stick upon one edge of the vessel and some other firm support, so that the stick is pointed straight towards the object at the bottom of the water. Then, keeping the stick in this line, shove it into the water toward the object. The end of the stick will be beyond the real object. Those who attempt to spear fish in this manner are sure to thrust the spear beyond the fish unless they make allowance for refraction.

Even when one looks straight down into the water, that is, along the normal to the surface, an object at the bottom is not seen at its true depth. The cause of this is apparent from Fig. 225. The rays from *O* on each side of the normal are bent away from each other on emerging from the water. The eye receives these rays and sees an image of *O* at *O′*. Since the index of refraction for water is $\frac{4}{3}$, an object in water is seen at $\frac{3}{4}$ of its true depth.

FIG. 225.



Apparent depth of water.

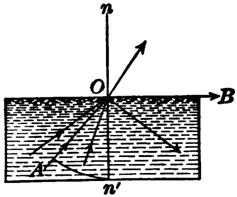
Experiment 55.

Focus a microscope upon a small black spot on a sheet of white paper. Place a piece of plate glass upon the spot and focus again. The distance the microscope is raised is the apparent elevation of the spot. In case of crown glass, the elevation is about $\frac{1}{3}$ of the thickness of the glass.

279. Critical Angle.—Total Reflection.

When light passes from a highly refractive medium into the air or other less refractive medium, the rays are bent from the normal. That is, the angle of refraction is larger than the angle of incidence. As the angle of incidence increases (Fig. 226), the refracted ray will bend farther from the normal. When the angle of refraction becomes 90°, *nOB*, the angle of incidence, *AOn′*, is called the *critical angle.*

FIG. 226.



The critical angle.

When the angle of incidence is greater than the critical angle, none of the light will emerge into the adjacent medium, but all will be reflected. This is called *total reflection.*

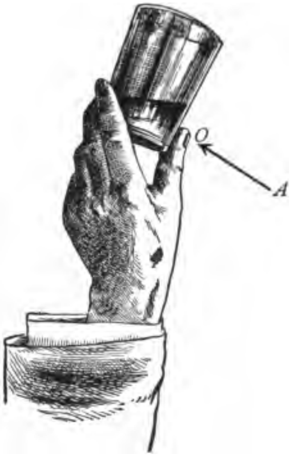
For light passing from crown glass into air, the critical angle is about 42°. For diamond, 24°. The brilliant play of light in a diamond is largely due to the total reflection of light which occurs when the angle of incidence exceeds this small critical angle.

The critical angle for light passing from water into air is about 48.5°.

Experiment 56.

Place a bright penny on the bottom of a thin drinking-glass. Cover with water to a depth of about 2 cm. Tip the glass toward you, keeping the penny to the opposite side. Look along *AO* (Fig. 227). The penny will appear to be at the surface of the water and will be very clearly seen. Explain this phenomenon on the principle of total reflection.

FIG. 227.



Total reflection.

280. Lenses.

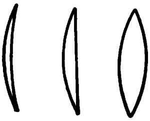
A lens is a body of transparent material, usually glass, with one or both sides curved. The kind discussed here are spherical lenses of crown glass.

There are two classes of lenses, the *convex* and the *concave.*

There are three kinds of convex lenses: *double convex, plano-convex,* and *concavo-convex* (Fig. 228).

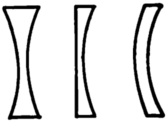
There are three kinds of concave lenses: *double concave, plano-concave,* and *convexo-concave* (Fig. 229).

FIG. 228.



Convex lenses.

FIG. 229.

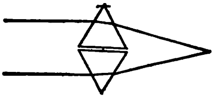


Concave lenses.

The general effect of convex lenses may be illustrated by placing two triangular glass prisms base to base as shown in Fig. 230. It is seen that rays of light passing through the upper prism are bent downward, and rays through the lower prism are bent upward. The prisms cause the rays to converge.

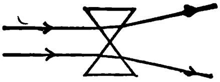
The general effect of the concave lenses is shown by placing the prisms vertex to vertex, as in Fig. 231. The upper prism now bends the rays upward, and the lower prism, downward. Thus the rays are made to diverge.

FIG. 230.



Principle of the convex lens.

FIG. 231.



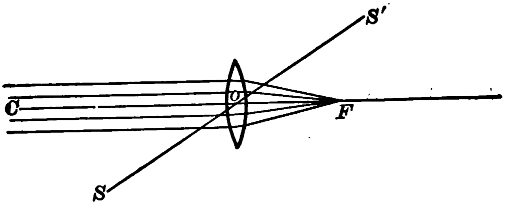
Principle of the concave lens.

A convex lens tends to collect the rays, while a concave lens tends to scatter them.

281. Definition of Terms.

The point O, Fig. 232, is called *optical center.* A ray of light passing through this point will enter and leave the lens in the same direction. This is because the tangents at the two points where the ray touches the surfaces are parallel. The ray will be bent toward the normal on entering the lens, but it will be bent just as much from the normal on leaving it. So the ray will be shifted slightly to one side but the direction will not be changed.

FIG. 232.



Definition of terms.

In double convex and double concave lenses the optical center is at the center of the lens. In plano-convex and plano-concave lenses it is at the center of the curved surface. In other lenses it is entirely outside the body of the lens.

The *center of curvature* is the center of the sphere of which the lens is a segment. Since the double convex lens consists of two segments, there are two centers of curvature, C and C'.

The principal axis is a line passing through the center of curvature and the optical center—COF.

A secondary axis is any line drawn through the optical center and not passing through the center of curvature—SS'.

The principal focus is the point where all rays parallel to the principal axis will meet after passing through a lens. In case of a convex lens the principal focus is real.

When the lens is concave, the focus is virtual and is at a point where the refracted rays, if extended backward, would meet.

The distance of the principal focal point from the lens depends on the curvature of the lens and the refractive power of the material. A lens made of crown glass, and another of flint glass, though they may have exactly the same form will not have the principal focus at the same distance from the lens, because flint glass has greater refractive power.

When the material of a lens is crown glass, the principal focus is very near the center of curvature. The lenses here considered are assumed to be made of crown glass.*

282. Images formed by Lenses.

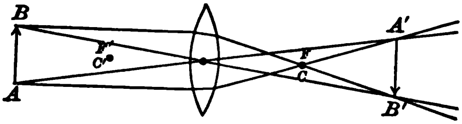
The place where the rays of light from any point meet or seem to meet is the location of the image of that point.

---

*Crown glass is a silicate of sodium and calcium, while flint glass is a silicate of potassium and lead.

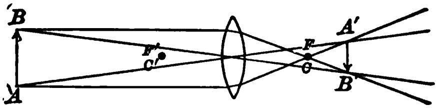
Just as in case of mirrors, two rays from any point are all that are needed to locate the image. The two most convenient are, one parallel to the principal axis and the other through the optical center. The former will, after refraction, pass through the principal focus, which in cases here considered, is at the center of curvature, and the latter will pass on through the lens without change of direction.

FIG. 233.



Object at twice the focal distance.

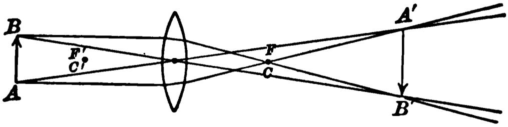
FIG. 234.



Object more than twice focal distance.

(1) When the object is situated at twice the focal distance. The drawing, Fig. 233, shows that the image is *real*, *inverted*, *same size as the object, and at the same distance from the lens.*

FIG. 235.



Object distance less than twice the focal distance.

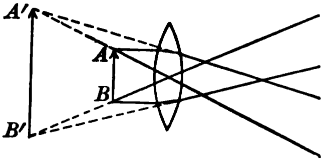
(2) When the object is more than twice the focal distance and less than an infinite distance, the image $A'B'$, Fig. 234, is *real*, *inverted*, *smaller than the object, and beyond the principal focus.*

(3) When the object is at a point less than twice the focal distance and greater than the focal distance, the image A'

B′, Fig. 235, is *real, inverted, larger than the object, and more than twice the focal distance from the lens.*

(4) When the object is at the principal focus, the rays after passing through the lens will be parallel, and no image will be formed.

FIG. 236.



Object distance less than the focal distance.

(5) When the object is between the principal focus and the lens, the rays will be made less divergent but not convergent. Consequently the image, *A′B′*, Fig. 236, is *virtual, erect and larger than the object.*

(6) When the lens is concave, diverging rays are always made more divergent, and so the image will be *virtual, erect, and smaller than the object*, as shown in Fig. 237, where *A B* is the object, and *A′B′* is the virtual image.

FIG. 237.

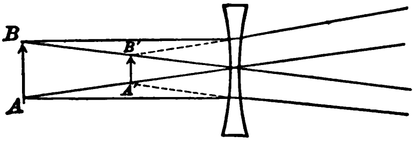


Image formed by concave lens.

283. Conjugate Foci.

Conjugate foci of lenses are two points such that if the object be placed at either one, the image will appear at the other. The object and image may exchange places. Illustrations are found in Figs. 233, 234, and 235.

284. Distance of Object, Image, and Principal Focus.

As in the case of spherical mirrors, if O is the object distance from a lens, I the image distance, and F the principal focal distance, then

$$\frac{1}{O} + \frac{1}{I} = \frac{1}{F}$$

If any two of these three distances are given, the other can be found by this equation. The distances may be measured from the surface of the lens.

Suppose that in a convex lens the principal focal distance is 15 cm. and the object is placed at a distance of 30 cm. Then

$$\frac{1}{30} + \frac{1}{I} = \frac{1}{15}$$

$$\therefore 15I + 450 = 30I$$

$$\therefore I = 30 \text{ cm.}$$

This is the case in § 282, 1.

Suppose that, using the same lens, the object be placed 10 cm. from the lens. Then

$$\frac{1}{10} + \frac{1}{I} = \frac{1}{15}$$

$$\therefore I = -30 \text{ cm.}$$

The negative sign indicates that the image is virtual. This is the case in § 282, 5.

This equation is also applicable to concave lenses, but in that case when either I or F are known, they are taken as negative quantities.

Suppose an object and its image are found to be, respectively, 30 and 10 cm. from a concave lens. Then

$$\frac{1}{30} - \frac{1}{10} = \frac{1}{F}$$

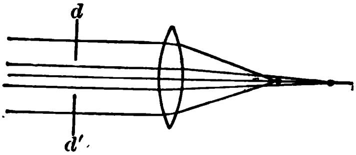
$$\therefore F = -15$$

The negative sign indicates that the focus is virtual. The I is considered negative because it is virtual (§ 282, 6).

285. Spherical Aberration.

In case of a spherical lens, the rays of light from a point of the object are not all brought to exactly the same point in the image. The rays farther from the principal axis are refracted more than those near this axis. As a consequence, the image is slightly blurred. To obviate this a disk with a hole through the center (*d d′*, Fig. 238) is placed in the path of the light. Only the central part of the lens is thus used and the image is more distinct. For this reason it is in most cases better, when taking pictures with a camera, to partially close the shutter or use the small aperture for the admission of light.

Fig. 238.

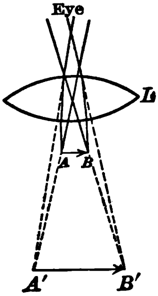


Spherical aberration.

286. The Simple Microscope.

A simple microscope in its simplest form consists of a single convex lens, *L*, Fig. 239. The essential fact in its use is that the object must be between the principal focus and the lens. The diverging rays from any point of the object *AB* will still be divergent, but less so after refraction. The image will be where the rays appear to meet when traced back along their directions after refraction. *A′B′* will be the image seen. It will be virtual, and larger than the object.

Fig. 239.



Simple microscope.

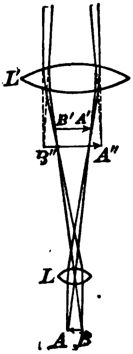
287. The Compound Microscope.

The compound microscope consists of two lenses, both convex, one in each end of a tube. The small lens at the lower end is called the *objective*, and the larger one, at the upper end, is called the *eye-piece.*

The objective forms a real image of *AB* at *A′B′* (Fig. 240), and the eye-piece is a simple microscope by which the image is enlarged.

The effect of the objective is like that explained in § 282, 3. The two lines from *A* intersect at *A′*, and the two from *B*, at *B′*. The image is then at *A′B′*, but this is not the image that is seen. The rays pass straight on and appear to come from *A′* and *B′*. When these rays pass through the lens *L′*, the effect is as explained in § 286. A virtual image is then seen at *A″B″*.

FIG. 240.



The compound microscope.

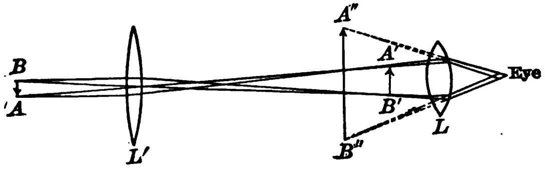
288. The Refracting Telescope.

The refracting telescope is in some respects like the compound microscope.

There are two lenses, L′, called the *objective*, and L, called the *eye-piece*. In the telescope the objective is much the larger lens. The objective forms a real image, *A′B′*, and this in turn is magnified by the eye-piece.

Since the purpose of the telescope is to view objects at a great distance, the effect of the objective will be that explained in § 282, 2. The objective, then, does not magnify the object. That is done by the eye-piece. It is necessary, therefore, that a great deal of light be collected at *A′B′*, so that when this image is highly magnified by the eye-piece the virtual image *A″B″* may be clearly seen. The objective of the Yerkes telescope is 40 inches in diameter, and that of the Lick telescope, 36 inches.

FIG. 241.



The refracting telescope.

289. The Opera-Glass.

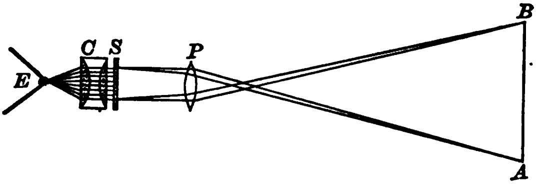
The opera-glass in common use has a convex lens for the objective but a concave lens for the eye-piece. By this arrangement the image is not inverted.

The lens would make a real image of the object, but before the rays meet to form this image a concave lens is interposed. This causes the rays to diverge, and so a virtual and erect image is seen. Illustrate by a drawing.

290. The Projection Lantern.

The projection lantern consists of the several essential parts shown in Fig. 242. *E* is an intense light, such as the electric arc or lime light. *C* is a *condensing lens*, usually composed of two plano-convex lenses, with the convex sides toward each other. The purpose of this lens is to direct a large quantity of light through the transparent *slide*, *S*. The light then moves on through the *projection lens*, *P*, where it is refracted, and thus a real, inverted, and large image is formed on the screen *AB*.

FIG. 242.



Projection lantern.

291. The Camera.

The essential parts of a camera are a box which is tightly closed, shutting out all light except that which is admitted through a convex lens in one side, and a sensitized photographic plate in the other end of the box. The plate must be adjusted to such a distance from the lens that the image will fall exactly upon it.

After *exposure* and *development*, a permanent record of the image will be found upon the plate in black and white. This plate is called a *negative*, because where the object is black the plate is white, and *vice versa*. By *printing* from the negative a *positive* is secured in which the shades of black and white are as they are in the object.

No method has yet been devised by which the color of objects may be directly photographed.

292. The Eye.

The optical structure of the eye is the same as that of the camera. The lenses are the *cornea* and the *crystalline lens.* The *retina* of the eye takes the place of the sensitized plate of the camera. The retina, however, cannot change its distance from the lens, but the crystalline lens will change its convexity for objects at different distances, and thus the image is formed on the surface of the retina.

293. Color.

Color is a sensation caused by the difference in the length of the light-waves.

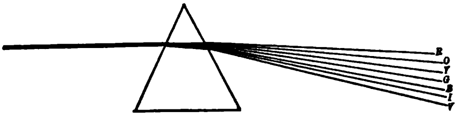
Difference in color in light is similar to a difference in pitch of sound.

Just as certain vibration frequencies in sound are selected to form the diatonic scale, so light waves of certain lengths have received the names,—*red, orange, yellow, green, blue, indigo,* and *violet.* The longest light waves give the sensation of red, and the shortest, violet.

294. Dispersion.

The light from the sun, the electric arc, and other sources, is called white light. In it the waves of every variety of length are all mingled together. If a beam of white light is passed through a refracting medium such as a triangular

FIG. 243.



Dispersion of light.

prism of glass, the rays will be separated from each other and made to spread out in a fan-shaped form, as in Fig. 243. This is called *dispersion* of light.

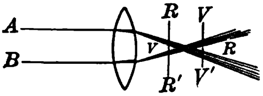
The cause of dispersion is the fact that the light having the shortest wave-length is most retarded by the glass and consequently is most refracted. The longest rays give the sensation called red. Hence the red light is least refracted. The next is the orange, then the yellow, green, blue, indigo, and, finally, the violet, having the shortest waves.

295. Chromatic Aberration.

When white light is passed through a spherical lens, dispersion as well as refraction occurs. This causes a separation of the white light into its various colors.

Thus, Fig. 244, the beam *A* will he refracted and dispersed downward, while the beam *B* will be affected in the same manner but bent upward. If a white screen, *RR'*, be placed in the path of the rays at the place shown, there will be seen several colored rings, red on the outside and violet within. If the screen be shifted to *VV'* the position of the colors is reversed.

FIG. 244.



Chromatic aberration.

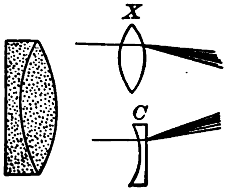
The light passing through the lens near its edge is most refracted and dispersed and hence causes the greatest display of color. When the rays are confined to the central portion of a thin lens, chromatic aberration is not so pronounced.

296. Achromatic Lens.

A good lens, suitable for accurate and delicate work in optical instruments, must, as far as possible, be free from both spherical aberration (§ 285) and chromatic aberration. The first effect is secured fairly well by use of a diaphram which shuts out all rays except those through the central portion of the lens.

Chromatic aberration is corrected by use of an *achromatic lens.* This lens consists of two pieces, a concave lens of flint glass, and a convex lens of crown glass. The dispersive power of the flint is nearly twice as great as that of the crown. They disperse the light in opposite direction, as shown at *C* and X (Fig. 245), one being concave and the other convex.

FIG. 245.



The achromatic lens.

When light passes through both, the dispersion of one will be corrected by the other. The crown glass lens is *double-convex* while the flint lens is *plano-concave.* Consequently light passing through both will be refracted toward the principal axis and a real image will be formed without chromatic aberration.

297. The Spectrum.—Wave Lengths.

The band of colors resulting from the dispersion of a beam of light is called a *spectrum.* It is called a *solar spectrum* when sunlight is used.

The gradual change of color from red to violet is a result of the gradual change in the wave length.

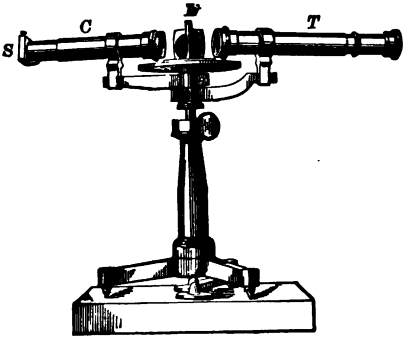
The approximate length of the waves for the seven colors of the spectrum, and the number of waves per second, are given below.

Color.	Wave length in millimeters.	Number of waves per second.
Red	.000762	393,000,000,000,000
Orange	.000656	458,000,000,000,000
Yellow	.0005896	510,000,000,000,000
Green	.000527	570,000,000,000,000
Blue	.000486	618,000,000,000,000
Indigo	.000429	697,000,000,000,000
Violet	.0003968	756,000,000,000,000

298. The Spectroscope.

The spectroscope is an instrument used in the examination of the spectrum. It consists of three essential parts as shown in Fig. 246. *L* is the *glass prism*, *T* is a *telescope*, and *C* is a *collimator*. A slit, *S*, at the outer end of the collimator admits a band of light. This slit is at the principal focus of a convex lens at the other end of the tube. The rays which issue from the collimator are, therefore, parallel. These rays then pass through the prism and are dispersed, causing a spectrum which may be viewed by the telescope.

FIG. 246.



The spectroscope.

299. Kinds of Spectra.

There are three classes of spectra, (1) *continuous*, (2) *bright line* or *discontinuous*, and (3) *reversed* or *absorption*.

A continuous spectrum is one in which there is a continuous blending of the colors from red to violet.

A bright line spectrum is one in which bright lines appear here and there across the spectrum, part of the colors being absent.

A reversed or absorption spectrum is one in which there are dark lines across the spectrum.

The dark lines are due to the fact that when light passes through a gas or vapor, that light is absorbed whose wave length is the same as that which would be emitted by the gas or vapor if it were heated to incandescence. The incandescent gas, alone, would give a bright line where there is now a dark line.

The solar spectrum contains many dark lines. They are called *Fraunhofer lines.* The sun is surrounded by gases and vapors which are not so incandescent as the body of the sun beneath them. The light from the bright part of the sun is thus partly absorbed and dark lines appear on the spectrum at the places where the vapors, if sufficiently heated, would produce bright lines. These vapors are sufficiently heated to give out light, but, by contrast, their lines in the spectrum appear dark.

By observing the dark lines produced by the vapor of iron, nickel, copper, and other substances, it is possible, by comparing these lines with the Fraunhofer lines, to determine many of the substances that exist in the sun.

Continuous spectra are produced by incandescent solids, liquids, or dense gases and vapors.

Bright line spectra are produced by rarefied gases and vapors when heated to incandescence.

Reversed or absorption spectra are produced when light is partly absorbed in its passage through vapors.

300. The Rainbow.

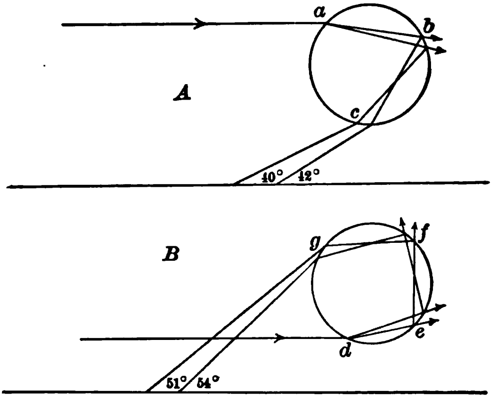
A rainbow occurs when the sunlight is refracted, reflected, and dispersed by a great number of rain drops.

While a drop of water is falling it is very nearly spherical.

A beam of light entering the drop at *a*, Fig. 247*A*, is refracted and passes to *b*. Here a part of the light passes out of the drop and a part is reflected to *c*. At *c* the light is again refracted and dispersed on passing out into the air, the red being least refracted.

In Fig. 247*B*, the light coming to the drop at *d* is refracted and dispersed, then passes to *e*, is reflected to *f*, thence to *g*, At *g* the light is again refracted and dispersed. In this drop the light is twice reflected and some of the light passes out of the drop each time. Consequently the colors are not so bright as in *A*.

FIG. 247.

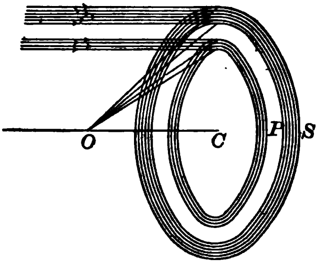


Light refracted and reflected by rain drops.

All the drops of a rain-cloud affect the light in the manner just explained. It is only at a certain angle, however, that the light is reflected to the eye of an observer.

The observer must be located on a line between the sun and the center of the bow, as at *O*, Fig. 248. This condition most frequently obtains when the sun is in the west and the rain-cloud in the east.

FIG. 248.



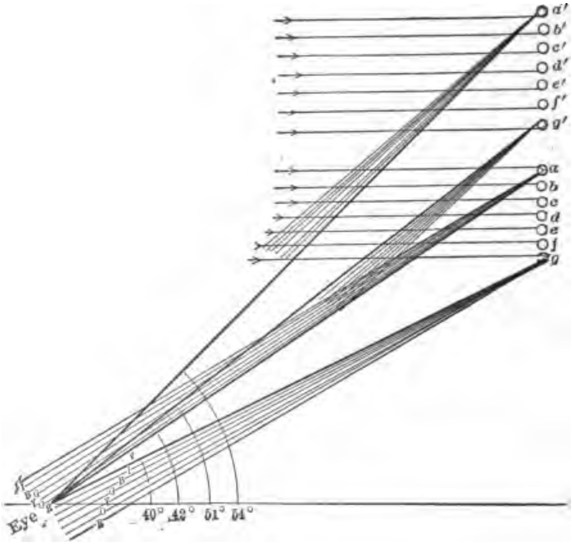
The rainbows.

The sun is so far distant that its rays are practically parallel to *oc*.

The circle of drops, *P*, affect the light, as explained in Fig. 247*A*. This light returns to the eye of the observer at *O*, the red ray making an angle of 42° with *OC*, and the voilet, 40°. This is the *primary bow.*

Outside of this circle is another circular band of drops in which the light is affected as in Fig. 247*B*, and these rays are also returned to the observer at *O*. In this case the angle made by the red ray with *OC* is 51° and that by the voilet ray 54°. This is the *secondary bow.* It is not so bright as the primary because the light is twice reflected within the drop, some light passing out each time.

Fig. 249.



The rainbow.

Although only the red and voilet rays are mentioned in this description, it must be understood that the other colors of the spectrum range themselves in proper order between these two extremes.

It should also be understood that each drop of the rain-cloud upon which the sunlight falls produces the effect shown at both *A* and *B*, Fig. 247, but only certain drops will return the light to an observer at a fixed point.

No two persons can see exactly the same bow.

In Fig. 249, let the eye be placed so that it will receive the red ray from the drop *a*. Since red is refracted least, all the other colors will pass above the eye. The drop *b* is below *a* and so the red ray from it will pass below the eye and the orange will enter the eye. The light from *c* will bring yellow to the eye, and so on to *g* from which voilet reaches the eye. In this bow, then—the primary—the red is at the outer rim of the circle and the violet at the inner rim.

The eye in this same position also receives red from *g′* and the other colors are below the red. Therefore the drop *f′*, above *g′*, sends orange to the eye ; *e′*, yellow ; *d′*, green ; and so on to *a′* from which the eye receives violet. Thus, in the secondary bow, red is on the inner side of the circle and violet outside.

A bow forming a complete circle is seldom observed because the center of the circle is so close to the horizon. If the sun is low and an observer is on the top of a mountain peak, a rainbow forming a complete circle may be seen.

An observer in the right position may see a rainbow in the spray from a lawn-sprinkler, or in the numerous drops of a cascade or fountain.

301. Characteristics of Different Wave Lengths.

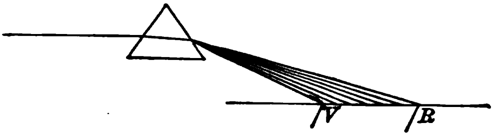
Light-waves which produce different colors also show different physical and chemical effects. Red is the color which has the greatest heating effect.

Experiment 57.

Pass a beam of light from an arc lamp through a horizontal slit in front of a stereopticon. Place a triangular prism in the path of the beam and throw a spectrum upon a sheet of white paper placed horizontally.

Place the bulb of one thermometer in the red, and that of another in the violet, Fig. 250. The former will show a much greater rise in temperature.

FIG. 250.



Heat effect of the spectrum.

This is as we would expect, because the only difference between heat-waves and light-waves is their length. Red light has the longest waves of all the colors, and hence its waves are most nearly like those of heat.

Waves of violet light have the greatest *actinic* effect That is, they are most active in producing chemical changes.

Experiment 58.

Let the spectrum fall upon a piece of sensitized paper. The paper may be secured of any dealer in photographic supplies. "Solio" paper is very good for this experiment. Only a small spectrum should be used so that the light at any point may be as intense as possible.

In course of several minutes it will be found that the paper upon which the band of violet and blue rested will have turned brown, while the place upon which the red fell will not be appreciably changed.

Red or "ruby" light is used in the "dark-rooms" of photograph galleries because such light is practically without actinic effect.

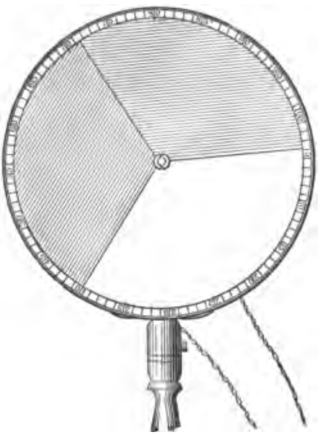
Photographs taken in the forenoon require less time of exposure to light, as a rule, than those taken in the afternoon. The light is less obstructed by vapor and particles of dust in the air early in the day and hence is richer in the upper colors of the spectrum.

Yellow is the most brilliant of the colors. A yellow object can be most distinctly seen. A house painted a bright yellow is very conspicuous. War-ships, during times of war, are painted a dull color that they may not be so readily sighted by the enemy.

302. Limits of Vision.

Light-waves of a certain length (§ 297) will produce the sensation of red, orange, yellow, green, blue, indigo, or violet. These colors constitute the visible spectrum. There are, however, other waves which are longer than those which produce the sensation of red. They are called *infra red* rays. There are also other waves which are shorter than those producing the sensation of violet. These are called *ultra violet.* The infra red and the ultra violet rays belong to the spectrum but they produce no sensation when they fall upon the retina of the eye. This is due to the structure of the eye.

FIG. 251.



Mixing colors.

It has already been shown that the perception of sound is confined to a certain range of wave-lengths or vibration numbers (§ 233).

It is now seen that the perception of light is also limited, being confined to wave-lengths from red to violet.

303. Mixing Colors.

When waves of light of different length are made to fall upon the eye at the same time, the process is called *mixing colors.* When the light is composed of all colors, it is called white light. Disks upon which are various combinations of color will, when rapidly rotated, produce a mixture of the colors. An impression upon the retina of the eye lasts for a short time—about $\frac{1}{7}$ of a second. While the disk is rotating, then, the impression from one color does not die out before another is impressed upon the same part of the retina. This results in a mixture of the colors. This persistence of vision is observed when a stick with a coal of fire on the end of it is whirled about, causing the appearance of a continuous circle of light.

Experiment 59.

Disks of various colors may be cut from cardboard. If holes be punched in the center and a slit be cut from the center out to one side, one card may be slipped upon another so that various proportions of either color may be exposed. If the cards be then rotated by means of a motor or rotator of any kind, the effect of the mixture may be observed.

A mixture of blue and yellow will produce the sensation of white. Not a bright white, but a light gray. White is also produced by the proper mixture of violet and yellowish green, or of red and bluish green. Several pairs of colors thus mixed will produce the sensation of white. Such colors are called *complementary*.

Experiment 60.

Hold a blue card, about 6 inches square, against a white wall. Look steadily at it for a short time and then jerk it away. The portion of the wall which was covered by the card will then appear yellow.

Any color of the spectrum may be produced by the proper mixture of *red*, *green* and *violet*. For this reason these have been called the three *primary color sensations*.

304. Mixing Pigments.

The mixing of pigments, or paints, is a process very different from the mixing of colors. A pigment may be of such a character that it will reflect all the waves of white light; it is then called white. It may absorb all waves except red, and it is then called red pigment, or paint. It may reflect only the blue and absorb all other waves, and so on.

When two pigments are mixed, only those waves will be reflected which are not absorbed by the mixture. Thus a mixture of yellow and blue pigments will produce green, and not white as in case of a mixture of colors.

305. Color of Objects.

The color of an object is determined by the kind of light which comes from it to the eye. A rose is red only in the sense that all other colors are absorbed by it and only the red is reflected.

An object which absorbs all colors is black, that is, it has no color. If it reflects all colors, it is white. The color does not reside in the object. The light must first fall upon it and be reflected thence to the eye.

A red rose will appear black except when waves of red light fall upon it.

Objects which are usually white will reflect light of any wave-length and consequently their color will be that of whatever color they receive.

Experiment 61.

Project a spectrum upon a white screen. Place strips of paper of various colors in the different colors of the spectrum. Notice that each strip has the same color that it would have in white light only when it is in the light which it is able to reflect.

Problems.

1. If the radius of the earth's orbit is 93,000,000 miles, what time will be required for light to pass from the sun to the earth?
Ans. About 8⅓ min.

2. A board 8 inches square is held between a light and a screen, 12 inches from the light and 2 feet from the screen. What will be the area of the shadow? *Ans.* 4 sq. ft.

3. A point of light is 6 m. from the wall of a room. A board 10 cm. square is held between the light and the wall. How far from the light must the board be placed that the shadow may be 1 m. square?
Ans. 60 cm.

4. What is the comparative intensity of the light at a distance of 1 m. and at a distance 4 m. farther from the source? *Ans.* 25 : 1.

5. In the use of the Rumford photometer it was found that a lamp at a distance of 122 cm. from the screen, and a standard candle at a distance of 34 cm. produced similar shadows. What was the candle power of the lamp? *Ans.* 12.9.

6. In the use of a Bunsen photometer it was found that the screen was equally illuminated when the lights were placed at 40 and 80 cm. If the light at a distance of 40 cm. is 3 c. p., what is the c. p. of the other? *Ans.* 12.

7. If a ray of light is incident upon a mirror at an angle of 60°, and the mirror is turned through an angle of 10°, what will the angle of reflection then be? *Ans.* 70°.

8. If the light from an object travels 50 cm. to a mirror, then 100 cm. to a second mirror, then to the eye, how far back of the second mirror will the image be formed? Make drawing. *Ans.* 150 cm.

9. How many images will be formed by two mirrors placed at an angle of 20°? *Ans.* 17.

10. An object is placed at a distance of 30 cm. from a concave mirror. The image is then found to be 10 cm. from the mirror. How far is the principal focus from the mirror? *Ans.* 7.5 cm.

11. The radius of curvature of a concave mirror is 30 cm. An object is placed 10 cm. from the mirror. How far from the mirror will the image be formed?

Ans. —30 cm. The minus sign indicates that the image is virtual.

12. If the principal focal distance of a concave mirror is 10.5 cm., and an object is placed 17 cm. from the mirror, what will be the distance of the image? *Ans.* 27.46 cm.

13. What is the relative index of refraction for light passing from crown glass into diamond? *Ans.* $\frac{5}{3}$.

14. If one looks down into water in a direction perpendicular to the surface, what is the apparent depth when the real depth is 12 feet? *Ans.* 9 feet.

15. If the distances of the conjugate foci from a convex lens are 50 and 150 cm., what is the principal focal distance? *Ans.* 37.5 cm.

16. An object is placed 60 cm. from a concave lens. The principal focal distance is 25 cm. Find the image distance. *Ans.* —17.65.

17. If the "shutter" of a camera is opened for $\frac{1}{100}$ of a second, how many waves of violet light will enter in that time? See § 297.

CHAPTER XIV.

MAGNETISM.

306. A Definition of Magnetism.

Magnetism is the molecular condition of metals by virtue of which they will attract or repel other metals.

A metal in this condition is said to possess magnetic properties and is called a *magnet.*

The only metal that possesses this property in a marked degree is iron in some of its forms, chiefly wrought iron, cast iron, and steel.

307. Lodestone.

Lodestone is a natural magnet. It is an iron ore called *magnetite.*

The name *magnet* had its origin in the word *Magnesia*, the name of a place in Asia Minor where strong natural magnets were found. If a long piece of this ore be suspended by a thread fastened to its center, it will turn so that one end will point toward the north and the other end toward the south. Thus it would lead or direct, and hence the name lodestone.

FIG. 252.

Lodestone.

308. Kinds of Magnets.

Magnets may be classified as *natural* and *artificial.* Natural magnets are composed of the iron ore just described. Artificial magnets are those which are manufactured. There are three kinds,—*permanent magnets, temporary magnets,* and *electro-magnets.*

309. Permanent Magnets.

Magnets made of hard steel are permanent magnets. These may be straight bars or bent in form of a horse-shoe.

A sewing needle or pieces of a watch-spring become permanent magnets when they are stroked upon lodestone or other magnet.

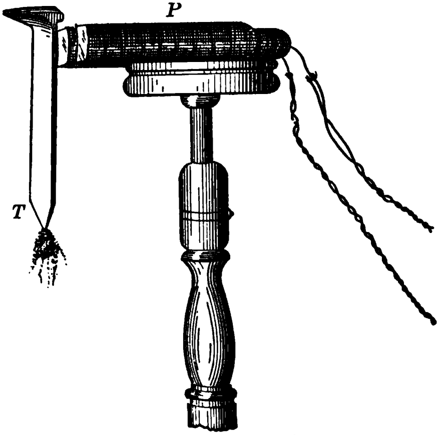
Experiment 62.

Place a piece of clock-spring upon a board and stroke it from end to end with one end of a strong magnet. The stroke must be made in one direction only and should be repeated several times. The spring will be strongly magnetized.

310. Temporary Magnet.

A temporary magnet is a piece of soft iron which is under the influence of some magnetizing force. Thus, as shown in Fig. 253, *T* is a bar of soft iron attracted to the magnet *P.*

FIG. 253.



Temporary magnet.

T will then attract pieces of iron as long as it is influenced by the magnet. As soon as *P* is removed, *T* will cease to be a magnet. The bar *T* is a temporary magnet.

311. Electro-Magnet.

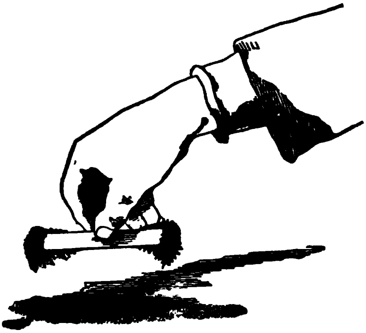
An electro-magnet is one in which a mass of iron is made magnetic by passing a current of electricity around it. Soft iron is used in this kind of magnet, and so it is a magnet only while the current flows. The electro-magnet will be explained more fully in a later chapter. It is an essential part of a dynamo, electric motor, telegraph, and numerous other electric appliances.

312. Poles of a Magnet.

If a bar magnet be plunged into iron filings and then lifted, as shown in Fig. 254, a mass of filings will cling to the ends of the bar, but not to the middle of it.

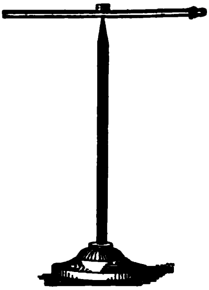
The ends are called the *poles* of the magnet.

FIG. 254.



Poles of a magnet.

FIG. 255.



Bar magnet balanced on a pivot.

If a bar magnet be placed horizontally and supported on a pivot so that it may freely turn, it will take a position nearly parallel to a geographical meridian of the earth,—that is, it will stand north and south.

The end toward the north is called the *north-seeking pole*, or *positive pole*.

The end toward the south is called the *south-seeking pole*, or *negative pole.*

The poles are usually marked N or +, and S or —.

The former is also often called the *red pole*, and the latter the *blue pole.*

A magnet must have at least two poles.

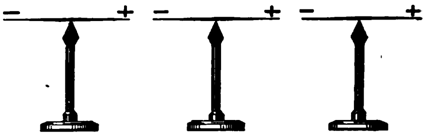
313. Magnetic Needle.

A magnetic needle is any thin bar of steel which is strongly magnetized and mounted at its center so that it may freely turn. The best needles have an agate bearing upon a fine steel point, so that the friction may be very slight. Others are suspended by a fine silk fiber.

314. Law of Magnetic Attraction.

When two magnetic needles are placed near to each other it is found that they will always turn and come to rest with the + pole of one next to the — pole of the other. If one needle be turned so as to bring + next to + or — next to —, the other needle will turn end for end, so that two unlike signs may be together.

FIG. 256.



Law of magnetic attraction.

Like poles of magnets repel, and unlike poles attract each other.

315. Test for Magnetism.

If it is desired to test whether or not a given piece of iron is magnetized, the same may be done by use of a magnetic needle. A piece of iron which is not magnetized will attract either end of the needle, but if the iron is magnetized it will attract one end and repel the other. Or, the iron may be turned end for end and presented to the same end of the needle. If one end attracts and the other repels, the iron is magnetized.

316. Theory of Magnetism.

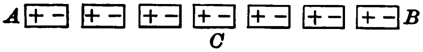
A theory of magnetism which accounts fairly well for the phenomena observed, assumes that each molecule is a magnet and, of course, has a positive and a negative pole.

If a slender piece of steel be magnetized and then broken in two, each half will be a magnet having positive and negative poles, as may be shown by the test described in § 315. If each half be now broken in two and these pieces be broken into smaller and smaller pieces, each piece, however small, will be a complete magnet. There is no reason to believe that this would not be the case even when the particles of steel are as small as the molecules.

By this theory, then, a body is magnetized when the greater part of the molecules have their positive poles all turned in the same direction, and their negative poles in the opposite direction.

In Fig. 257 let the seven oblongs represent seven molecules of a magnet. The positive pole of each is nearer to *A* than the negative poles are. The negative poles are all nearer to *B* than the positive poles are. Consequently, at *A* there is the combined effect of all the + poles, and at *B*, all the — poles. *A* is then the positive end of the magnet because the positive poles of each molecule are nearer than the negative poles to that end. For a similar reason *B* is the negative end of the magnet.

FIG. 257.

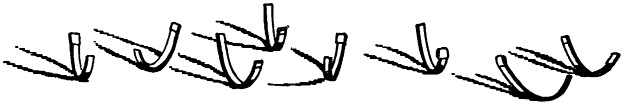


Small magnets.

This theory also affords an explanation of the fact that iron filings are not attracted by the middle of a magnet (§312). It is seen, in Fig. 257, that each pole on one side of *C* has a corresponding opposite pole at the same distance on the other side of *C*. The molecules at the center of the magnet are just like those at the ends, but the opposite poles of all the molecules are, from that point, at an equal distance from any outside body, and hence their effect is neutralized.

This theory also furnishes an explanation of the process of magnetizing a piece of iron or steel. The molecules are magnets whether the whole bar shows magnetic effects or not. In a bar of iron that is not magnetized the molecules are not arranged in any definite order. When a magnet is drawn along the bar all the like poles of the molecules are turned in the same direction. In Fig. 258 is shown a number of small magnets made of pieces of a watch-spring. They are turned in various directions and there is no order in their arrangement. Each may be taken to represent a molecule of an unmagnetized piece of iron. The white end of these small magnets are positive.

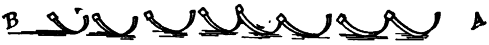
Fig. 258.



Small magnets representing molecules.

If, now, the negative end of a strong magnet be moved above these small magnets from *A* to *B*, Fig. 259, all the + ends will be turned toward *B*, and all the — ends toward *A*. The operation described in Experiment 62 may now be explained in accordance with this theory.

Fig. 259.



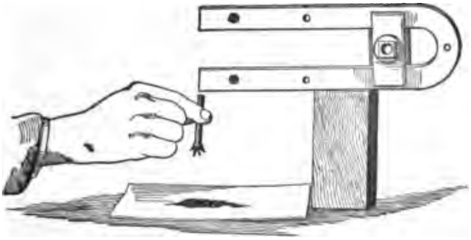
Molecules in magnetized iron.

When the metal is steel, the molecules will retain their position after they are once turned so that their like poles are all in the same direction. For this reason steel is used in making permanent magnets. In case of soft iron the like poles of the molecules point in the same direction only while some magnetizing influence is present.

317. Magnetism by Induction.

A magnet may induce, or cause, magnetism in a bar of iron without actually coming in contact with it. This is called magnetism by induction. As shown in Fig. 260, the iron rod is magnetized by the horse-shoe magnet, although they do not touch each other. The filings hanging from the lower end of the rod show that it is magnetized.

FIG. 260.



Magnetism by induction.

318. Lines of Force.

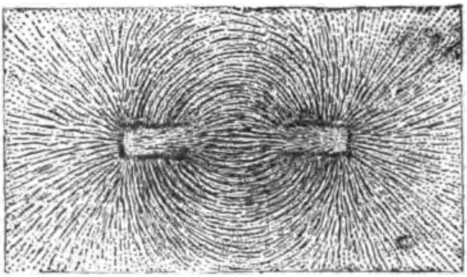
The region in which the magnetic forces act is called the *magnetic field.*

When any pieces of iron or steel come within this field they are acted upon by the magnet.

If a card is placed upon the two poles of a horseshoe magnet and iron filings are then sifted evenly upon the card, the filings will arrange themselves as shown in

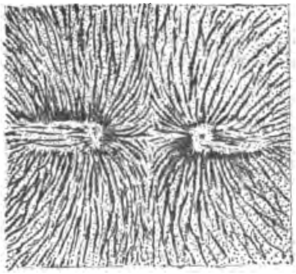
Fig. 261. Similar results will be observed when unlike poles of two bar magnets are placed beneath the card. Lines appear to curve from one pole to the other. These are called *lines of force.* The lines of force are not the filings themselves but the paths along which the rows of filings are arranged. They come from the positive and enter the negative pole.

FIG. 261.



Lines of force between two unlike poles.

FIG. 262.



Lines of force between two like poles.

If a small compass is placed at any point upon one of the lines, the needle will stand in the direction of the line at that point.

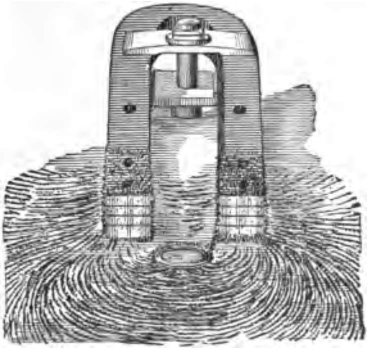
When two positive poles or two negative poles are brought near to each other so that their magnetic fields overlap, the lines of force do not pass from one of the poles to the other. The relation of the lines may be shown by the iron filings on a card, as in Fig. 262.

319. Magnetic Substances.

Substances that are magnetized when placed in a magnetic field are called magnetic substances. Iron in its various forms is the chief magnetic substance. Nickel and cobalt are magnetic, but only slightly so as compared with iron.

A substance is said to be *permeable* when lines of force may be readily set up within it. Soft iron is very permeable. In Fig. 263 the ring of soft iron is placed between the poles of a strong horse-shoe magnet. As shown by the filings, the lines of force turn from their usual path and crowd together in the soft iron of the ring.

FIG. 263.



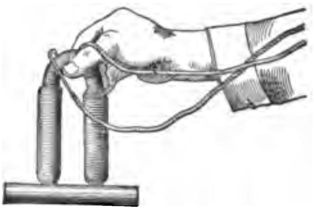
Permeability.

320. Insulators of Magnetism.

There is no insulator of magnetism. That is, there are no substances which will prevent the passage of lines of force. When a plate of soft iron or steel is placed upon the poles of a horse-shoe magnet, the lines are deflected from their course and will, for the most part, pass within the permeable iron from one pole to the other. If a piece of iron is now placed upon the plate, it will be only slightly attracted by the magnet. The plate has not prevented the passage of lines of force but has furnished an easy path by which they may pass from the positive to the negative pole. In this way an object may be screened from lines of force.

For example, if a watch is enclosed in an iron case the lines of force will pass through the case and the watch will not be magnetized.

Fig. 264.



Action of magnet on iron filings within a glass tube.

Lines of force will pass freely through non-magnetic substance. Magnetic force is not screened by glass, rubber, porcelain, or any other non-magnetic substance. If a glass tube is filled with iron filings, the filings will be strongly attracted by the magnet although the glass intervenes.

321. Magnetic Polarity of the Earth.

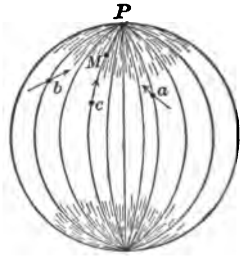
The earth affects a magnet just as one magnet affects another. The earth is, therefore, a magnet.

The magnetic poles of the earth, however, are not at the same place as the geographical poles. The north magnetic pole is at a point near Baffin's Bay, and the south magnetic pole is on the opposite side of the earth near the south geographical pole.

The north magnetic pole is in latitude about 70° north. It is, then, more than 1000 miles from the north geographical pole.

322. Declination.

Fig. 265.



Declination.

Declination is the angle made by a magnetic needle with the geographical meridian at that place. Let *P*, Fig. 265, be the north geographical pole, and *M* the magnetic pole.

A magnetic needle at *a* will point toward *M*, and so to the west of *P*. The needle at *b* will also point toward *M*, and so to the east of *P*. The angles made by the needles with their geographical meridians are called the angles of declination at those points. Those lines along which the angles of declination are equal are called *isogonic lines.*

The needle at *c* in the figure points toward *M* and also toward *P*. There is, then, no declination at *c*. The line along which there is no declination is called an *agonic line.*

The agonic line for the Western Hemisphere passes through the eastern part of the United States. This is not, however, a fixed line, but shifts as the magnetic pole changes. The pole appears to swing back and forth between eastern and western points. The period of this swing is probably nearly 400 years. The rate at which the declination changes is only a few minutes each year, but is not the same in different localities.

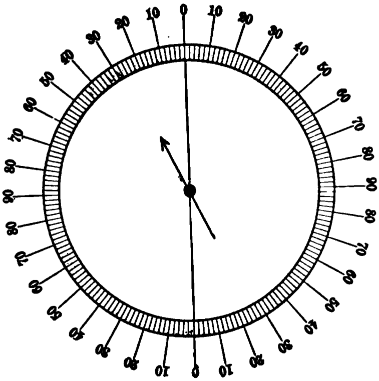
Experiment 63.

The angle of deviation for any locality may be found by drawing upon the floor or a fixed table, a true north and south line. This may be done by fixing two points so that they and the North Star will be in a straight line. If plumb bobs be then suspended from these points, the line connecting the points of the bobs will be the line sought. If a good magnetic needle be placed upon this line, the angle of declination may be observed.

323. Inclination.

Inclination, or dip, is the angle which the magnetic needle makes with a horizontal plane.

FIG. 266.



Angle of declination.

At the equator the dip is zero. As the needle is moved from the equator toward the north, the north-seeking pole of the magnet dips more and more. When the north magnetic pole is reached, the needle will stand in a vertical position. If the needle is carried from the equator toward the south pole, the south-seeking pole of the needle will dip more and more until it stands vertically over the south magnetic pole.

The inclination, or dip, in the latitude of New York is about 70°.

Lines along which the inclination is the same are called *isoclinic lines.* These correspond to parallels of latitude as the isogonic lines correspond to the geographical meridians.

CHAPTER XV.

ELECTRICITY.

324. The Known and the Unknown.

Many of the properties of matter and many of the laws of nature are definitely and certainly known. Many of these have been discussed in the previous chapters of this book.

This is the most valuable kind of knowledge, for if we know exactly what a thing will *do* we may use it intelligently though we may not know exactly what it *is*.

We do not know what matter is. We do not know the cause of gravitation or of magnetism. We do not know the exact nature of electricity, and many of the phenomena produced by electricity are as yet without an explanation.

The intense and powerful investigation of these subjects in recent times gives fair promise that many of these things will be known in due time. Such knowledge would be extremely valuable as a means of future discovery and would lead to a clear understanding of many common phenomena which we cannot now fully explain.

Although the exact nature and origin of electricity is not known, yet it is present on all sides and has become one of the greatest factors of modern life. Many of the properties and laws of electricity have been found out by experiments, by experience, and by investigation. These are the things which are discussed in this chapter.

325. Origin of the Word "Electricity."

Electricity in one form or another has always been present in the natural world. Lightning and the Northern Lights are displays of electricity on a grand scale. These are as old as the world, though it was not known until modern times that they were electrical in their nature.

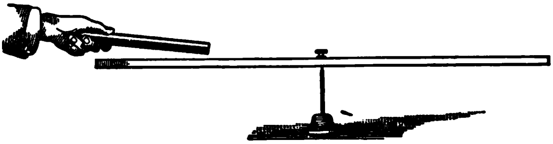
Many bodies when rubbed one upon another will be electrified. The mere stroking of the fur of animals on a cold, dry day, produces electric phenomena which must have been observed in the very earliest times.

It was not until about 600 B. C. that the Greeks noted and recorded the fact that a mineral called *amber* will, when rubbed, draw other light bodies to itself. The Greek word for amber is *electron*, and from it we now have the words *electric*, *electrical*, and *electricity*. These words had a very limited application until recent times. During the last thirty years the field of electricity has so rapidly widened that the word now has a meaning never dreamed of by early observers.

326. Attraction by an Electric Charge.

If a stick of rosin is rubbed with fur, a piece of flannel, or any kind of woolen goods, it will be strongly electrified.

FIG. 267.



Attractive force of an electrified stick of rosin.

If the rosin is then held near some object which is free to move, the attraction may be observed. As shown in Fig.

NOTE.—The rosin may easily be moulded into a cylindrical stick. Select a piece of stiff paper about one foot square. Roll it in form of a tube having about one inch internal diameter. Close one end with a cork. Tie strings about the tube to hold it in shape. This tube is the mould. Melt about one pint of rosin and stir into it about one-half ounce of beeswax. The wax will make the rosin less brittle. Then pour the rosin into the mould and set aside to cool. Remove the tube by unrolling the paper. The rosin may be thus moulded into a convenient form. Two or more sticks of rosin should be prepared in this manner.

267, a piece of pine about one meter long is mounted on a sharp point in the manner of a magnetic needle. If the electrified rosin is now held near, the pine stick will be attracted and may be made to rotate. Similar phenomena may be observed when the rosin is held near pith balls or bits of tissue paper. Any body which is not itself electrified will be attracted by the rosin. A smooth stream of water flowing from a water tap will be drawn aside when the rosin is held near.

327. Positive and Negative Charges.

There are many substances which, when rubbed together, will become electrified. The nature of the charges, however, are found to be different. When the stick of rosin is rubbed with fur, or woolen goods, both the rosin and the fur are found to be electrified. These charges are opposite in character. That on the rosin has been called *negative*, and that on the fur *positive*. Whenever two bodies are charged by rubbing one upon the other, one of the charges will be positive and the other negative. If glass is rubbed with silk, the glass will have a positive charge and the silk negative. If sulphur is rubbed with silk, the sulphur is negatively charged, and the silk positively.

328. Law of Attraction and Repulsion.

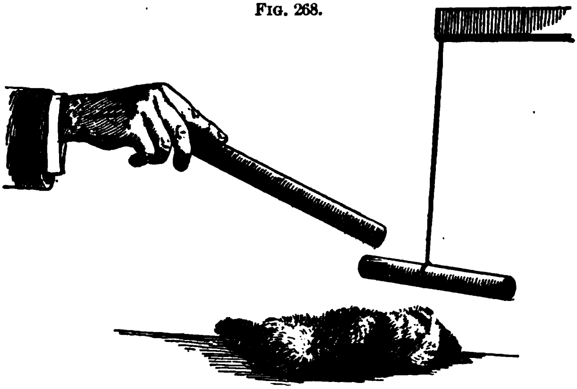
The behavior of bodies containing like or opposite charges may be observed by suspending one so that it is free to rotate and then bringing the other near to it. Thus, as shown in Fig. 268, two sticks of rosin have been negatively charged by rubbing them with fur. In this case it is found that one will *repel* the other. If, now, a glass rod is rubbed with silk and held near the suspended rod of rosin (Fig. 268) the rods will be drawn together.

Bodies having unlike charges of electricity are attracted to each other.

Bodies having like charges are repelled from each other.

Bodies which are not charged are attracted by either a positive or a negative charge.

FIG. 268.



Attraction and repulsion of electrified bodies.

329. Methods of Charging a Body.

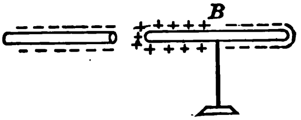
A body may be charged with electricity in three different ways. By *rubbing*, by *induction*, and by *contact*.

(1) The method by rubbing has already been explained.

(2) A body may be charged by induction by simply bringing it near to another body which is already charged.

If a brass cylinder *B*, Fig. 269, is mounted on a glass stand, and the stick of rosin containing negative electricity is held as shown, the positive electricity in *B* will be drawn toward the rosin while the negative electricity will be repelled. *B* is thus charged by induction. If, now, the stick of rosin, which contains the inducing charge, is removed, the two opposite charges in *B* will neutralize each other. But as often as the inducing charge is returned, the two opposite charges will be found in *B*.

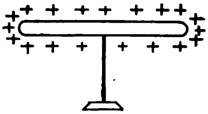
FIG. 269.



Charging by induction.

If, while *B* is in the condition shown in Fig. 269, it is touched with the finger, the charge which is being repelled will escape and only positive electricity will remain. If the stick of rosin is now removed, the positive electricity will be distributed over the whole surface of *B*, as shown in Fig. 270. *B* is then permanently charged by induction. This induced charge is always opposite in sign to that of the inducing charge.

FIG. 270.

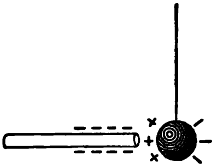


Charged by induction.

(3) A body may be charged by coming in contact with a charged body. The charge received is the same in kind as that of the body from which it is taken.

If a pith ball is suspended by a silk string and brought near to a body charged with either positive or negative electricity, the ball will at first be electrified by induction, as explained above, and as shown in Fig. 271. The opposite kinds of electricity then being nearer to each other than the like kinds, attraction will be greater than repulsion and the bodies will be drawn together. When contact occurs, the positive electricity of the ball will, in this case, be neutralized, and the ball will take on a charge of electricity of the same kind as that of the charging body. It is then found that the ball is repelled in accordance with the law for like charges. The pith ball is thus charged by contact.

FIG. 271.



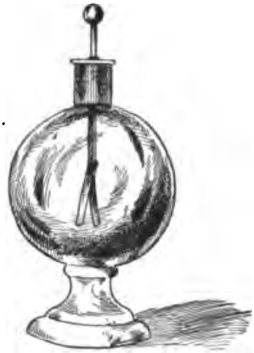
Charging by contact.

330. The Electroscope.

The electroscope is an instrument used in detecting charges of electricity. It consists essentially of two gold leaves hanging side by side or of a single gold leaf hanging by the side of a vertical metal plate. The leaves are enclosed in a glass case and are attached to a metal rod which ends in a ball or disk on the outside of the case.

The principle involved in the use of this instrument is that whatever kind of electricity one leaf receives the other leaf will receive the same kind, for they are connected to the same rod. According to the law, like charges repel each other, and so the leaves will be spread apart or made to diverge by either a positive or a negative charge.

Fig. 272.



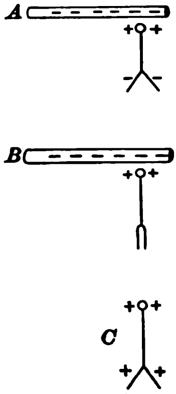
The electroscope.

Gold leaves are used because leaves of this metal can be made very thin and so they will be moved by a very slight force. Leaves of tissue paper or of aluminum foil may be used, but they will not move for very small charges of electricity.

331. Charging the Electroscope.

It is frequently desirable to charge the leaves of an electroscope with either positive or negative electricity. This may be done by induction. If the electrified rod of rosin is held above the knob of the electroscope, the first effect is as represented in Fig. 273, (*A*). By touching the finger to the knob, the negative electricity, being repelled by the rosin, will escape, but the positive is bound by the attraction of the negative charge on the rosin (*B*). If now the stick of rosin is removed, the positive charge will distribute itself over the leaves as well as over the knob, and the leaves will diverge (*C*). The electroscope is now charged positively. In a similar manner, by use of a glass rod which has been rubbed with silk, the electroscope may be charged negatively.

Fig. 273.



Charging the electroscope.

332. To determine whether a Charge is Positive or Negative.

A body charged with either kind of electricity will, when brought near an electroscope, cause the leaves to diverge, but this instrument may also be used to determine the kind of electricity. One method of doing this is described in the following experiment:

Experiment 64.

Charge the electroscope either positively or negatively by induction (§ 331). Care must be taken not to bring the electrified rod too close to the knob. A rod of rosin or hard rubber is best for charging. After rubbing the rosin with fur, approach the electroscope slowly from a distance of several feet. When the leaves stand at about an angle of 90° to each other, touch the knob lightly with the finger or a metal rod, then remove the inducing charge. The leaves will then be charged positively if the inducing charge was negative, but negatively if the inducing charge was positive. Now let any unknown charge be brought slowly toward the knob. If the divergence of the leaves increases, the charge is of the same kind as that in the leaves. If the divergence decreases, the charge is of the opposite kind.

333. Potential.

Electric potential is the condition of a body in reference to its ability to give electricity to other bodies. This may also be illustrated by the difference of level of two vessels of water (Fig. 274). The pressure at the bottom of the vessel *A* is much greater than that on the bottom of *B*. The condition is such that *A* is able to give water to *B*. If the stopcock in the tube connecting the bottoms of the vessels be opened, water will flow from *A* to *B* until the surfaces in both vessels are at the same level.

FIG. 274.

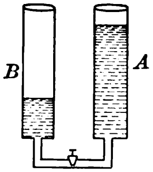
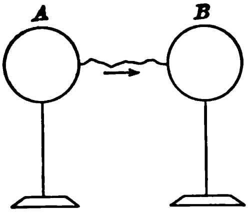


Illustration of difference of potential.

This difference between two charges of electricity is called a *difference of potential*. Suppose, for example, that two brass spheres, Fig. 275, contain charges of electricity having a difference of potential. Let the potential of *A* be higher than that of *B*. If the two are then connected by a wire, electricity will flow from *A* to *B*, and while it is flowing it will do work just as water will do work in flowing from a higher to a lower level.

FIG. 275.



Flow of electricity resulting from a difference of potential.

That which causes the electricity to flow is called *electromotive force* or, in short, E. M. F. The E. M. F. is caused by difference of potential.

The flow of electricity will continue until there is no difference of potential, just as the water continued to flow until there was no difference of level.

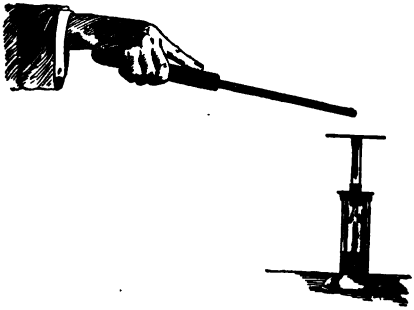
The two charges considered may be both positive or both negative, and yet have a difference of potential in relation to each other. The earth is assumed to have zero potential for purposes of reference, just as zero on a thermometer is a point of reference in measurement of temperature. A charge of electricity having a higher potential than that of the earth is called positive. If lower than that of the earth, negative. The flow of electricity is from positive to negative.

334. Conductors.

A body upon which electricity will readily pass from one point to another is called a *conductor of electricity*. Bodies which strongly resist the passage of electricity are called *nonconductors*. Materials differ greatly in this respect. All metals are conductors, silver and copper being the best. Glass, rosin, and hard rubber are examples of nonconductors. This subject of resistance and conductivity is treated more fully in a later section.

The rod of rosin which has been used in the experiments described above is a nonconductor. When it is charged by rubbing, the electricity does not flow from it to the hand or other body which it may touch. If it is touched with the finger, the charge at that point only will be removed. The whole charge may be removed by rubbing the hand over all parts of the rod. This, however, is not the case with a metal rod. A rod of brass, for example, will be electrified if it is rubbed with fur. But if the rod is held in the hand, the charge will not be detected, for it will flow away as fast as it is produced. If, however, the rod is fastened to a handle of some nonconducting material, such as glass or hard rubber, and then rubbed, the charge will be shown by the electroscope (Fig. 276).

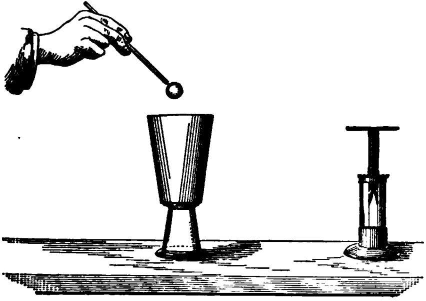
FIG. 276.



Metal rod electrified by rubbing.

335. Charge only on Outer Surface. When a conductor is charged with either positive or negative electricity, the charge is found to be only on the outer surface. If a metal vessel is placed upon an insulated support, as shown in Fig. 277, and charged by touching it several times with the charged rosin or by use of an electrophorus, the position of the charge may be tested. This may be done by use of a *proof plane.* This is a small metal disk with smooth

FIG. 277.

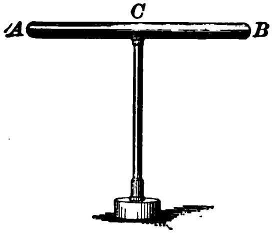


Electric charge found only on the outer surface of a vessel.

edges, fastened to an insulating handle. If the proof plane is touched to the outer surface of the vessel and then held near the knob of the electroscope, the gold leaves will diverge. If the disk is then discharged by touching it with the finger and a test be made of any point on the inner surface of the vessel, no divergence of the gold leaves will be observed.

This is as might be expected, for since like charges repel each other, each portion of the charge will be driven as far as possible from other portions.

FIG. 278.



Distribution of the charge.

336. Distribution of the Charge on a Conductor.

A charge of electricity will distribute itself equally over the surface of an insulated metal sphere. But if the conductor is not spherical, the charge will be most intense at the points having the greatest curvature. In a body like that shown in Fig. 278 the charge will be crowded toward *A* and *B*.

337. Effect of Points.

Since the charge of electricity crowds toward that part of a conductor which has the greatest curvature, we find, as we would expect, that the intensity of the charge at a fine point is very great.

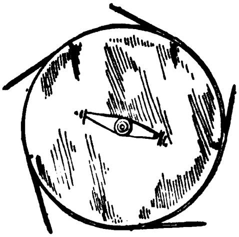
Experiment 65.

Operate the electric machine, § 340, and adjust the distance of the discharging knobs so that frequent sparks are produced. Fasten a pin or needle at right angles to the end of a glass rod and place the head of the needle on one knob with the point projecting toward the other knob. The sparks will then cease. Remove the needle and sparks will again occur. Separate the knobs so that sparks do not pass between them. Place the head of the needle upon one of the knobs and pointing forward to the flame of a candle. The flame will be bent from the needle as by a draft of air.

In the experiment just described, the intense charge at the point of the needle electrified the air and dust-particles near by with the same kind of electricity. These like charges repel each other. It is then a case of action and reaction in which the air does all the moving. The needle did not stop the discharge between the knobs. It produced a constant and steady discharge without a spark. Sparks occur when the electricity accumulates and the difference of potential becomes great enough to force the electricity through the intervening air. In this case the discharge occurs all at once.

The action and reaction may be shown by use of the apparatus shown in Fig. 279. This consists of a light metal disk to the edge of which is soldered a number of pin-points in the position shown. The whole is mounted so that it may readily rotate. If this apparatus is placed upon a plate of glass and connected by a wire to one knob of the electric machine, the disk will rapidly rotate. In this case the air is not only driven from the points but the points themselves are driven in the opposite direction.

FIG. 279.



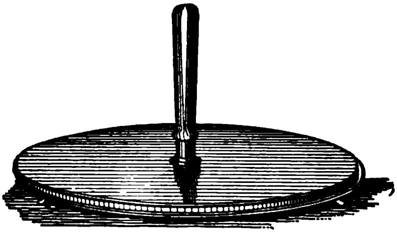
The electric whirl.

The purpose of the knobs on the electric machine, the electroscope, and other instruments of this kind is to prevent the escape of the electricity.

338. The Electrophorus.

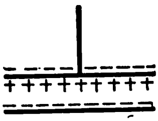
The electrophorus consists of a plate usually made of rosin or hard rubber, and a metal disk with an insulating handle. The operation consists in rubbing or striking the rosin plate with fur or a woolen cloth and then charging the metal disk by induction (§ 329). This is done by placing the metal disk upon the charged plate, touching it lightly with the finger, then lifting it by the handle. If the plate had a negative charge the disk will be charged positively. The explanation of this phenomenon is similar to that given in section 331. If the rosin plate, the lower one, Fig. 281, is charged negatively, it will act inductively upon the metal plate above it, attracting the positive and repelling the negative electricity. If the finger is now touched to the metal plate, the negative will escape, for it is being repelled, but the positive is bound by the lower plate. When the metal plate is removed from the influence of the charge beneath it, it is found to contain a positive charge, and if brought near to the knuckle or other conducting body a spark will occur.

FIG. 280.



The electrophorus.

FIG. 281.



Principle of electrophorus.

The operation may be repeated again and again without recharging the lower plate.

339. The Electric Field.

The region around a charged body is called the electric field. This is the field in which a charged body is capable of exerting a force. The field may be mapped out by imaginary lines of force just as in case of the magnetic field (§ 318). These lines issue from the positive charge and end at the negative. They are the directions along which

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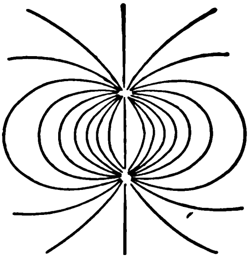
(NOTE.—Minute directions for making a cheap but efficient electrophorus may be found in the "First Book of Physics.")

a positive charge will be moved. This may be illustrated by use of a pith ball suspended from a fine silk thread. The ball will be charged by contact with one of the charged bodies and will then be repelled along one of the lines of force to the other oppositely charged body.

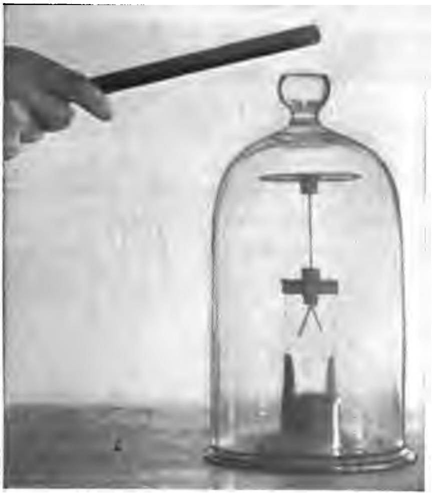
FIG. 282.



Lines of force between two bodies having unlike charges.

When a conductor of any kind is brought into the electric field the direction of the lines of force may be modified in a manner similar to the effect of soft iron on magnetic lines (§ 319). There is no substance which will prevent the passage of lines of force. For example, glass will prevent the passage of electricity but it does not prevent the influence of the electric charge. An electroscope may be charged by induction while a heavy plate of glass intervenes between it and the charging body.

FIG. 283.



Influence of the electric charge through glass.

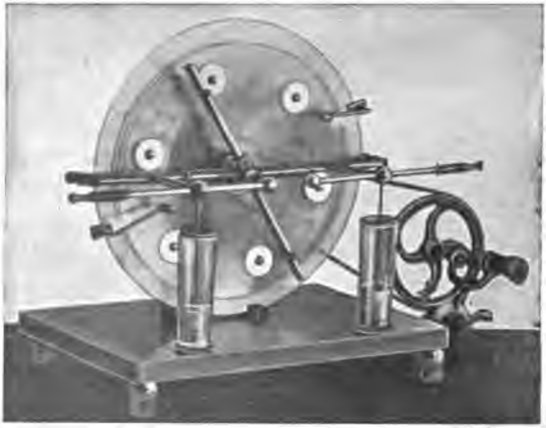
Experiment 66.

Place a heavy bell-jar over the electroscope, as shown in Fig. 283. Bring the charged stick of rosin to within about one meter. The divergence of the gold leaves shows that the glass does not prevent the influence of the charge.

340. Electric Machines.

Various machines have been devised for producing electric charges such as have been described. The electrophorus is a good though not very convenient form of electrical machine. That shown in Fig. 284 is a modified form of the Holtz machine, so named from its inventor. It may be considered a continuous electrophorus, for while one of the plates is rotating a continuous difference of potential will be produced although a steady discharge may occur at the same time.

Fig. 284.

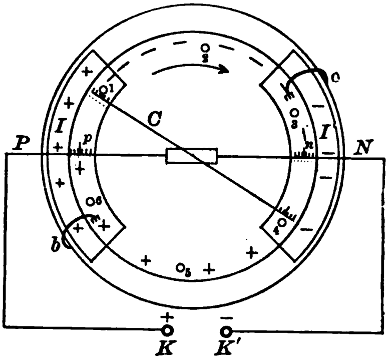


Electric machine.

The operation of this machine may be understood by reference to the diagram Fig. 285.

There are two glass plates, one stationary and the other mounted so that it may be rotated. The larger plate is stationary. On the stationary plate are pasted two pieces of paper, *I* and *I'*, called inductors. These correspond to the lower plate of the electrophorus. On the front of the rotating plate are fastened a number of metal buttons, 1, 2, 3, 4, 5, 6. These correspond to the metal plate of the electrophorus. The brass rod *C* carries a small wire brush at each end and these touch the buttons as they pass. This corresponds to the touch of the finger in the operation of the electrophorus.

FIG. 285.



Operation of the electric machine.

Let the inductor *I* be charged positively and *I'* negatively. These charges act inductively through the glass plates upon the buttons. Let the rotating plate be turned in the direction indicated by the arrow. The button 1 has just been charged by induction from the inductor *I* and by being touched by the brush at the upper end of *C*. It then carries a negative charge. All the buttons are charged in this manner every time they pass the brushes at the end of the rod *C*. While one button is being charged negatively, another at the other end of *C* is being charged positively.

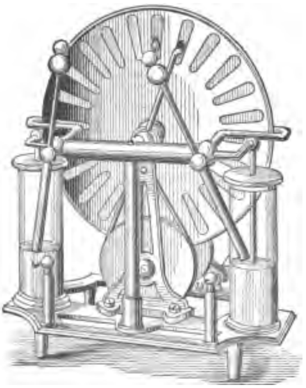
Conducting rods *a* and *b* are connected to the inductors and terminate in a metal brush in the path of the buttons. When the buttons touch these brushes, the electric charge of the inductors is increased.

The horizontal brass rods, *P* and *N*, are insulated from each other by the hard-rubber support at the center.

A number of fine points extend toward the rotating plate from the rods *P* and *N* and also from each end of *C*. The strongly charged inductors draw from these points any electricity of an opposite kind, but repel any of a like kind. Thus, negative electricity is drawn onto the surface of the glass from the points *p* and positive electricity is driven out on the rod *P* to the knob *K*. The points *n* operate in a similar manner, driving negative electricity to the knob *K′*. When the difference of potential between the sparks becomes sufficiently great, a discharge will begin, as will be indicated by the sparks.

Another machine, Fig. 286, was invented by Wimshurst. It consists of two plates of glass or hard rubber, which are made to rotate in opposite directions. A number of metallic sectors are fastened to the outer side of each plate. Two conducting rods, one in front of each plate, are set at right angles to each other. Metal brushes at the ends of the rods rub upon the sectors. The horizontal rods with the fine points are similar to those of the Holtz machine.

FIG. 286.



The Wimshurst machine.

The operation of this machine is similar in principle to that explained above.

The general principle involved in all electrical machines is that the energy employed in producing motion is expended in producing a difference of electrical potential. Whether electricity is generated by turning a Holtz machine or by rubbing a stick of rosin with fur, the result is brought about only by the expenditure of energy.

341. Condensers.

A condenser in its simplest form consists of two conducting plates with an insulating plate between them. For example, two sheets of tinfoil with a glass plate between them.

Any insulated conductor may be charged with electricity, but if another conductor, connected to the earth, be brought near, the capacity of the former will be greatly increased; that is, it requires much more electricity to produce the same difference of potential when a second conductor is near. These two conductors and the air or other insulating substance between them, constitute what is called a condenser.

The quantity of electricity required to charge a condenser to any given difference of potential depends on (1) the size of the conducting plates and (2) the nature of the material between the plates.

342. Dielectric.

The material used to separate the plates of a condenser is called the *dielectric.* The capacity of a condenser is different when different dielectrics are used.

The ratio of the capacity of a condenser when any given substance is used as a dielectric, to the capacity when the dielectric is air, is called the *specific inductive capacity* of that substance. The ratios for several common substances are given below.

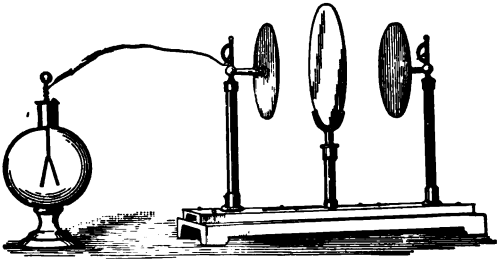
Air	1
Hard rubber	2.5
Paraffin	2.25
Shellac	3
Sulphur	3.5
Mica	6.5
Glass	5 to 10

The numbers following these substances mean that the capacity of a condenser will, other things being the same, be that many times greater than when air is the dielectric. The numbers are only approximate.

Experiment 67.

Support a disk of brass or other metal on an insulating stand. Connect it by a fine wire to an electroscope placed two or three meters distant. Charge the disk and electroscope. Then bring near to the disk another one of the same kind. Touch this second disk or connect it to the water tap. The leaves of the electroscope will partly collapse. This shows that the capacity of the disk is increased by the presence of the second disk.

FIG. 287.



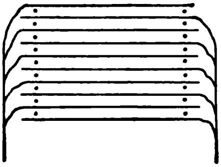
Change in capacity.

Insert a plate of glass or other dielectric between the disks, and the leaves will collapse still more.

343. Form of Condenser.

Condensers usually consist of a number of sheets of foil insulated from each other by glass, oiled silk, or mica. The alternate sheets of foil are connected as shown in the illustration. In this manner a condenser of large surface may be made in compact form.

FIG. 288.



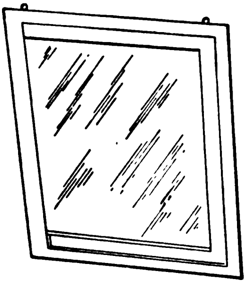
Form of condenser.

Experiment 68.

A simple form of condenser like that shown in Fig. 289, may easily be made. A plate of glass about 12 × 12 inches is covered on both sides with shellac. When the shellac is nearly dry, press upon each side a sheet of tinfoil about 10 × 10 inches.

If necessary, the foil may be made to adhere by pressing a warm iron upon it. This may be strongly charged by holding it between the discharging knobs of the electrical machine.

FIG. 289.

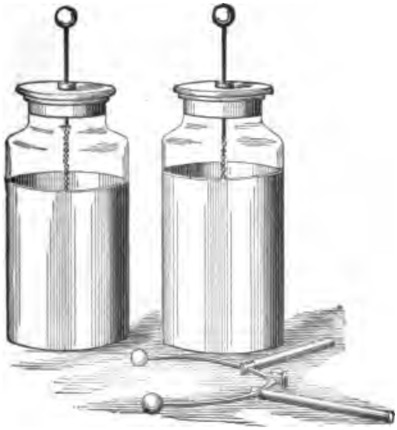


Glass plate condenser.

344. Leyden Jar.

The Leyden jar is simply a condenser in the form of a cylinder. The jar is coated with tinfoil both inside and outside to near the neck, as shown in the figure. The lid is some nonconducting material through which passes a metal rod. The rod ends above in a spherical knob and from its lower end hangs a chain which touches the inner coating of the jar.

FIG. 290.



Leyden jars.

The jar may be charged by repeatedly touching the knob with the charged plate of the electrophorus (§ 338), or by connecting the inner coating to one knob of the electrical machine and the outer coating to the other knob. There are many methods by which the jar may be charged.

345. The Discharge.

The discharge of a condenser is effected by connecting the plates having an opposite charge. This may be done by use of a wire or a discharger such as that shown in Fig. 290. In case of the Leyden jar, the connection is made between the outer coat and the knob. When the knob of the discharger is sufficiently close to the knob of the jar, a bright spark will be observed between the knobs. This discharge occurs whenever the difference of potential between the coats is great enough to overcome the resistance of the air between the knobs.

The discharge appears to be instantaneous and all in one direction. Such, however, is not the case. The discharge is oscillatory. It surges back and forth many times and with wonderful rapidity during the short time that the spark is observed. The number of oscillations depends on the size of the condenser. The smaller the condenser the greater the number of waves per second. The number may be as many as a thousand million per second.

346. Electric Waves.

The oscillations which occur at the time of the discharge set up waves, called electric waves, in the surrounding ether. These waves were discovered by Hertz of Germany and are often called Hertzian waves.

Electric waves possess all the properties of light waves and travel through the ether at the same speed. Such waves do not affect the retina of the eye because the shortest that can be produced are much longer than the longest waves of light. If electric waves of sufficient frequency could be produced, they would be light waves.

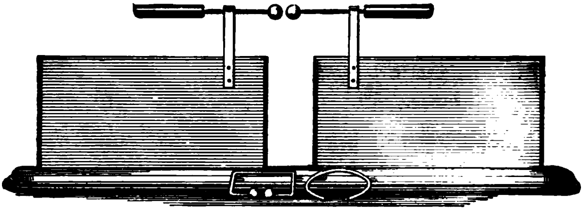
Experiment 69.

Electric waves may be detected by use of a copper wire or metal band bent in form of a circle, the ends being brought very close together.

If the ends of the wires are tipped with polished balls so much the better, but the balls are not indispensable in this experiment.

Mount two metal plates about 35×10 cm., as shown in Fig. 291. Charge the plates continuously by connecting one to one side and the other to the other side of an induction coil or an electric machine. Also bring the knobs attached to these plates near enough together so that there will be a continuous discharge. Hold the loop of wire near to and parallel to the plates. A small spark will pass from one end of the loop to the other when the distance is properly adjusted.

Fig. 291.

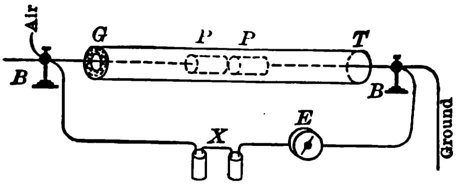


Apparatus for detecting electric waves.

347. Wireless Telegraphy.

Electric waves which are longer than those which produce light cannot affect the eye, but an eye, as it were, has been invented and by it such waves are detected. The *coherer* used in wireless telegraphy is a device of this kind. The essential parts of a coherer and its operation may be readily understood from the diagram, Fig. 292. *GT* is a glass tube in which are inserted two brass plugs, *PP*. Between the plugs are a quantity of filings of nickel or other material.

Fig. 292.



The coherer.

Wires lead from the plugs to binding posts, *B* and *B*. These posts are also connected through a battery, *X*, and an indicator, *E*. The filings lie loosely between the plugs and, in that condition, are a poor conductor. The battery circuit is thus broken by the filings. If, now, electric waves are intercepted by the air line and pass down through the filings to the ground, the filings *cohere* to each other and thus complete the battery circuit. The indicator *E* may be an electric bell, a telegraph sounder, or any instrument operated by an electric current.

By gently tapping the glass tube the filings are made to decohere as soon as the electric waves cease to pass through them.

This whole apparatus constitutes a *receiver* in its simplest form.

The *sending* apparatus, which may be hundreds of miles distant, consists of a condenser which is being constantly charged by some form of electrical machine and which may be discharged at will.

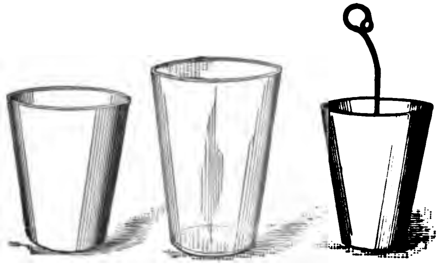
Thus any set of intelligible signals may be sent out as waves on the ether and may be detected by a receiver which is within the radius affected by those waves.

348. Location of the Charge of a Condenser.

The charge in a condenser resides in the dielectric and not in the coatings. This may be shown by use of a condenser with movable coatings. If this condenser is charged just as a Leyden jar is charged and the coatings are then removed, no electric charge will be found in the coatings though they may be handled or touched to each other. If, now, the coatings are put in place on the glass jar, and the outer coat connected by a discharger to the knob, a bright spark is observed.

If the condenser is again charged and the coatings removed, the charge may be found to be in the glass. As the hand is rubbed over the glass both inside and outside a slight tingling is felt and small sparks may be seen. The glass being a nonconductor, only those parts which are touched are discharged. If the hand is rubbed over the whole surface and the condenser again built up, it will be found that the original charge is entirely wanting. Thus it is shown that the charge resides in the dielectric. The coatings, being conductors, serve to distribute the charge to all parts of the dielectric.

FIG. 293.



Electric charge on the dielectric.

349. Lightning.

Lightning is the discharge of a huge condenser. The clouds on one side and the earth on the other, with a thick layer of air for the dielectric between them, constitute the condenser. Often two clouds and the air between them constitute the condenser. In the former case the stroke of lightning is between the clouds and the earth, and in the latter case between the two clouds.

In the present stage of electrical science no satisfactory explanation can be given of the origin of this immense charge, nor of the great difference of potential which is necessary to produce a spark one mile or more long. When the fundamental nature of electricity becomes a part of scientific knowledge, the phenomena of lightning will also be clearly explained.

Lightning in ancient times was attributed to evil spirits and angry gods, but when men began to experiment with electrical machines there arose a strong conviction that lightning and electricity are identical. The bright spark that is seen and the sharp sound that is heard when a Leyden jar is discharged appeared, on a small scale, to be counterparts of the phenomena of lightning.

In 1752 Benjamin Franklin performed his celebrated kite experiment, and the electricity which flowed from the cloud down the hempen cord behaved just like that from the electric machine.

Electricity itself is not visible but it renders the air through which it passes luminous, and hence its path can be traced. The very sudden rupture of the dielectric—the air—when electricity crashes through it, sets up air-waves of great intensity. These produce the sensation called thunder. When the stroke of lightning is near, the thunder is a sudden crash; but when at some distance, the waves are reflected back and forth between hills, clouds, or banks of air which are acoustically opaque, thus causing reverberation or prolonged thunder.

350. Lightning Rods.

Electricity flows from one point to another along the line in which the least resistance is offered to its passage. Hot air, for example, offers less resistance than cold air and, consequently, lightning often strikes down through the hot air in chimneys. Tall trees which are rooted in wet earth are frequently struck because they furnish a path of less resistance than the air.

Considerations such as these lead to the conclusion that a tree, a house, or other object, may be protected from lightning by erecting near by a path of less resistance.

All metals are conductors of electricity. Copper and iron are good conductors.

If a rod of copper or iron be fastened to the side of a building, the lower end being deep in the ground and the upper end extending above the building, then in case the lightning should strike at that place, it would follow the rod to the ground.

If the top of the rod ends in a number of fine points, these may prevent a stroke which would otherwise occur. (Here review § 337 and repeat the experiment there given.)

351. Static Electricity.

The kind of electricity thus far discussed in this chapter is often called *static* as distinguished from the *current* electricity which will be described in the remaining part of the chapter. These are, however, only different manifestations of one and the same thing. Static electricity is so called because it will *stand* on a nonconductor or on an insulated conductor. But it will also flow when two charges of different potential are properly connected.

The static charge is probably a condition in which the ether about a body is in a state of strain. While in this state the charge possesses potential energy just as a clock-spring, when wound up, is in a strained condition and possesses energy.

The flow of electricity from a point of higher to a point of lower potential is only an effort to relieve the strain and restore equilibrium.

When the strain is restored as fast as it is relieved, a constant flow of electricity is produced.

352. Source of Electric Currents.

Whenever there is a difference of potential between two points and these points are connected by a conductor, a current of electricity will flow. As long as the difference of potential is maintained, a current will continue to flow. This may be illustrated by the analogy of water flow between two vessels which are connected by an open pipe.

As long as there is a difference of level there will be a flow of water through the pipe.

Any machine or device which will create and maintain a difference of potential between two points, will cause a continuous flow of electricity through the conductor which connects those points.

There are three common and useful methods of producing this difference of potential: (1) The *electric machine* (§ 340); (2) *Chemical action*, that is, by use of batteries; (3) *Dynamos.*

In all cases energy must be expended in producing the condition which results in an electric current. Electricity is not energy but it contains the energy which was expended in producing the difference of potential. Water is not energy, but a body of water at a higher level or in motion possesses energy.

The electrical machine (§ 340) produces a large difference of potential and hence it forces the current along with great pressure, but the quantity of electricity which it produces in any given time is small. Hence this current has a very limited use.

Batteries ordinarily produce only a small pressure, or difference of potential, but a considerable quantity of electricity. Hence batteries are very useful for small electrical work.

The dynamo can be made to produce both a high pressure and a large current. Hence the dynamo is the most useful of electrical machines.

353. Electrical Terms.

The following short definitions are here given for present use. More extended definitions are given later (§ 377).

The strength of a current is defined as the quantity of electricity which passes any cross section of a conductor in a unit of time. It is the quantity rate at which electricity passes any point in a conductor.

The ampere is the practical unit by which the strength of a current is measured.

The ohm is the unit by which the resistance to the passage of a current along a conductor is measured. The resistance offered by 97.5 feet of No. 20 or 9.51 feet of No. 30 copper wire is very nearly one ohm. The exact definition is given in § 377.

Electromotive force is the force which causes an electric current to flow. It is often called electrical pressure from the analogy of pressure due to a head of water.

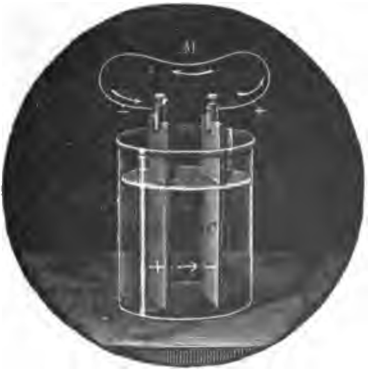
The volt is the unit by which the electromotive force (E. M. F.) is measured. The volt is such an electromotive force as will cause the flow of one ampere through a resistance of one ohm.

354. The Voltaic Cell.

The voltaic cell is so called from an Italian named Volta. (See cyclopedia.)

This cell consists of two plates, one zinc and the other copper, placed parallel and near to each other in a vessel of dilute sulphuric acid. A copper wire is attached to the upper edge of each plate. When the ends of the wires are

FIG. 294.



Voltaic cell.

connected to each other a current of electricity will flow and numerous bubbles of hydrogen will rise from the copper plate. After the current has been allowed to flow for some time, it will be found that the zinc plate is wasting away while the copper plate is not perceptibly changed.

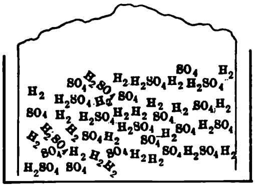
It will also be found that the sulphuric acid in the liquid is being changed to zinc sulphate.

355. Explanation of Action within the Cell.

A probable explanation of the action within the cell is as follows:

When sulphuric acid is dissolved in water a part of its molecules are broken up into *ions*. An ion is an atom or group of atoms possessing a charge of electricity. The symbol of sulphuric acid is H_2SO_4. This is separated into the ions H_2 and SO_4, the H_2 having a positive charge of electricity and the SO_4 a negative charge.

FIG 295.


SO_4 H_2
SO_4 H_2 SO_4 H_2 H_2SO_4 H_2 H_2SO_4 H_2
H_2 H_2SO_4 H_2 SO_4 H_2 H_2 SO_4 H_2
SO_4 H_2 H_2SO_4 H_2 H_2 SO_4 H_2SO_4 SO_4 H_2SO_4
H_2 H_2 SO_4 H_2 SO_4 H_2 SO_4 H_2
SO_4 H_2 H_2 SO_4 H_2 H_2 SO_4 H_2SO_4 H_2
H_2SO_4 SO_4 H_2

Ions in the voltaic cell.

It is assumed that these molecules are constantly separating into ions, and the ions as constantly recombining into molecules. Now if the plates of zinc and copper be set into the liquid, as shown in Fig. 295, there will be a movement of positive ions (H_2) toward the copper plate, and of negative ions (SO_4) toward the zinc plate. The hydrogen gives up its positive charge to the copper, and the sulphion (SO_4) its negative charge to the zinc plate.

A hydrogen ion does not move all the way from the zinc to the copper but may combine with the nearest SO_4 or may set free an H_2 in an H_2SO_4 and take its place. This H_2 then makes other combinations, but whatever movement the H_2 makes, its direction is always toward the copper plate. In a similar way the sulphion (SO_4) always moves toward the zinc plate.

The SO_4 combines with the zinc, forming $ZnSO_4$.

356. Parts of the Cell.

The two plates are called the *elements* of the cell. The element toward which the positive ions move is called the *cathode*. That toward which the negative ions move is called the *anode*.

The liquid is called the *electrolyte*.

The direction of the current is from the anode to the cathode in the liquid, and from the cathode to the anode in the wire.

The ends of the wires are called the *electrodes*. That attached to the cathode is the positive electrode, and that to the anode, the negative electrode.

357. Local Action.

Zinc is seldom used in a pure state. It contains many small particles such as carbon and iron. When it is placed in the electrolyte a short local circuit is formed between the zinc and the impurities. Thus the zinc is used up and no current from this source passes over the wires.

This local action may be prevented by amalgamating the zinc.

Experiment 70.

Cut a strip of zinc and copper each about a centimeter wide and ten centimeters long Fill a drinking glass about half full of acidulated water—about one part of sulphuric acid to fifteen parts of water. Place one end of the zinc strip in the acid and observe the chemical action as indicated by the hydrogen bubbles.

Place both strips in the acid and touch them together at the top. Bubbles will arise from both strips.

Lift out the zinc and smear a drop of mercury over that part which extends beneath the surface of the liquid. Place the zinc in the liquid again. No bubbles arise from it. Connect the tops of the strips and hydrogen appears at the copper strip only.

The mercury forms an amalgam with the zinc and thus pure zinc only is floated to the surface of the plate where the chemical action occurs.

358. Polarization.

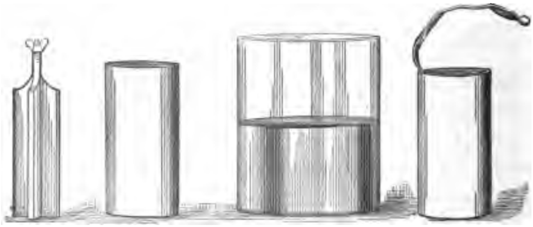
After a current from a simple voltaic cell has been allowed to flow for a short time it is found that the cathode is covered with a layer of hydrogen bubbles. The cell is then said to be *polarized.* The current grows weaker and weaker as polarization proceeds. The cathode, in this way, becomes practically a hydrogen plate. The current grows weaker because hydrogen is a poor conductor of electricity and also because there is less difference in the chemical action of the acid upon zinc and hydrogen than that upon zinc and copper. Two plates of zinc, copper, or other like metals will not cause any flow of electricity. The greater the difference between the elements in this respect, the better the cell.

One of the chief aims in the arrangement of the numerous cells which have been devised is to avoid polarization.

359. The Daniell Cell.

The elements in the Daniell cell are zinc and copper.

FIG. 296.



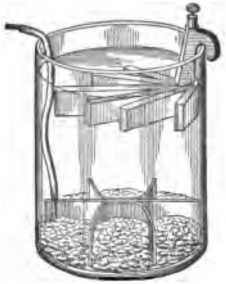
Parts of the Daniell cell.

The zinc is placed in a porous cup filled with dilute sulphuric acid. The cup is placed in the center of the jar.

A cylinder of sheet copper surrounds the porous cup and is immersed in a solution of copper sulphate. The porous cup separates the two liquids but does not prevent the passage of the ions.

The sulphion (SO_4) unites with the zinc, forming zinc sulphate, and free hydrogen ions pass through the walls of the porous cup on their way to the cathode—the copper. They never reach the copper because of the copper sulphate through which they must pass. The symbol for copper sulphate is $CuSO_4$. The free H_2 will displace the Cu and combine with the SO_4. The Cu then moves on to the copper plate where it is deposited as pure metallic copper. Thus the copper plate is kept clean and bright and polarization is entirely prevented. This cell then gives a current which is very constant, the E. M. F. being about 1.09 volts. Crystals of copper sulphate are put into the solution and these dissolve as fast as is necessary to renew the strength of the solution.

FIG. 297.



The gravity cell.

360. The Gravity Cell.

The principle of the well known *gravity cell* is exactly the same as that of the Daniell cell. In construction, however, the two liquids are kept apart by gravity, the copper solution being made strong, and the acid solution weak.

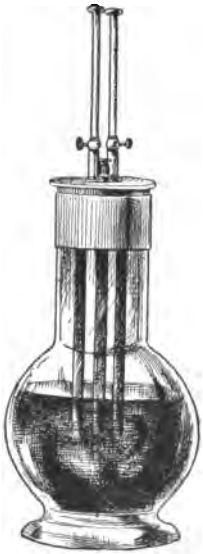
The acid then floats upon the copper solution. The anode and cathode can then be immersed in their proper liquids without the use of the porous cup.

361. The Bichromate Cell.

The bichromate cell is a type of cell in which polarization is, for the most part, avoided by the use of an agent which will oxidize the H_2, forming H_2O—water. The oxidizing agent in this cell is sodium or potassium bichromate. A saturated solution of this salt is made in water and about one-tenth of its volume of strong sulphuric acid is then added.

The elements are zinc and carbon. The zinc must be amalgamated. Chemical action in this cell continues between the acid and the zinc whether the circuit is closed or not; hence provision is made for lifting the zinc out of the solution when the cell is not in use.

FIG. 298.



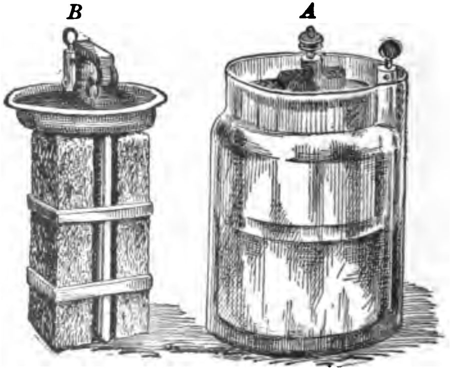
The bichromate cell.

This cell will give a vigorous current for a short time. The E. M. F. is about 2 volts but the current is not constant.

362. Leclanché Cells.

These cells are made in various forms. The elements are zinc and carbon. The liquid is a solution of ammonium chloride (sal ammoniac). The oxidizing agent is manganese dioxide. One form of this cell is shown in Fig. 299*A*, where the carbon element is placed in a porous cup and surrounded with granules of the manganese dioxide.

FIG. 299.



Leclanché cells.

In Fig. 299*B*, the carbon dioxide has been pulverized, mixed with shellac, and pressed into the form of prisms. The prisms are bound to the carbon by rubber bands.

This cell gives an E. M. F. of about 1.46 volts. It is a very serviceable cell for any open-circuit work—that is, for such work as ringing bells, operating telephones, and so on, where the current is in use for only a short time.

363. Dry Cells.

The principle of the dry cell is similar to that of the Leclanché, but the electrolyte is made into a paste. The essential part of the paste is ammonium chloride. The cup itself is made of sheet zinc. The carbon, with manganese dioxide packed around it, occupies the center of the cup, and the paste occupies the space between.

The E. M. F. is about 1.3 volts.

This is a very convenient cell for all open-circuit work.

364. Zinc as a Fuel.

Since, as has been observed, zinc is the element which is consumed, we must conclude that the energy in the electrical current results from the chemical action between the zinc and the electrolyte. The zinc, then, may be considered a fuel just as coal is a fuel in the chemical action between carbon and oxygen in combustion,

Zinc, however, is an expensive fuel in comparison with coal, so that primary cells, such as have been described, cannot compete with the dynamo in the production of powerful currents.

365. Ohm's Law.

Ohm's law states that *the strength of a current varies directly as the electromotive force and inversely as the resistance.* This may be stated concisely in the equation

$$C = \frac{E}{R}$$

where C is the strength of the current in amperes, E is the E. M. F. in volts, and R is the resistance in ohms. When any two of these quantities are given, the third may easily be found. Thus, if C is 10 amperes and R is 5 ohms, then

$$10 = \frac{E}{5}$$

$$\therefore E = 50 \text{ volts.}$$

366. Resistance of Conductors.

The resistance of a conductor can be calculated when its dimensions and the character of its material is known.

The law of electrical resistance is as follows:

The resistance to the flow of an electric current varies directly as the length and inversely as the area of cross section of the conductor. Resistance is also different for different materials.

This law is stated concisely in the equation

$$R = \frac{Kl}{d^2}$$

where R is the resistance in ohms, l is the length in feet, and d is the diameter, in mils, or thousandth of an inch.

The areas of circles are to each other as the squares of their diameters, and hence d^2 can be used for area, the unit area being a small circle one mil in diameter.

The specific resistance is represented by K. It is a constant quantity for the same material under the same conditions. In this equation it is the resistance of one *mil foot*, that is, it is the resistance of a wire one foot long and one mil in diameter.

The specific resistance varies with a change of temperature, but for a number of common conductors the values of K are approximately as follows:

Silver	9.53
Copper	10.35
Gold	13.34
Zinc	36.46
Platinum	58.00
Iron	63.00
Lead	127.20
German silver	135.00
Mercury	616.16

Suppose it is desired to find the resistance of 75 feet of copper wire whose diameter is .02 inch.

By a simple substitution of these values in the equation,

$$R = \frac{10.35 \times 75}{20^2}$$

$$\therefore R = 1.94 \text{ ohms.}$$

The value of d must be in thousandths of an inch. In the example above, d is equal to 2 *hundredths* or 20 thousandths, and so 20 is the number to be squared.

367. Internal Resistance of Cells.

The resistance offered by the electrolyte to the flow of electricity from anode to cathode in a voltaic cell is called *internal resistance.* The resistance offered by the wires and instruments through which the current is made to pass is called *external resistance.*

The law given in the section above applies as well to internal resistance. If the plates of a cell are moved farther from each other the internal resistance is increased in the same proportion as the distance has been increased. Also if the size of the plates are increased the internal resistance is decreased, because this is the same as the increase in the area of cross section of the conductor.

368. Arrangement of Cells.

A number of cells properly joined together constitute a *battery.*

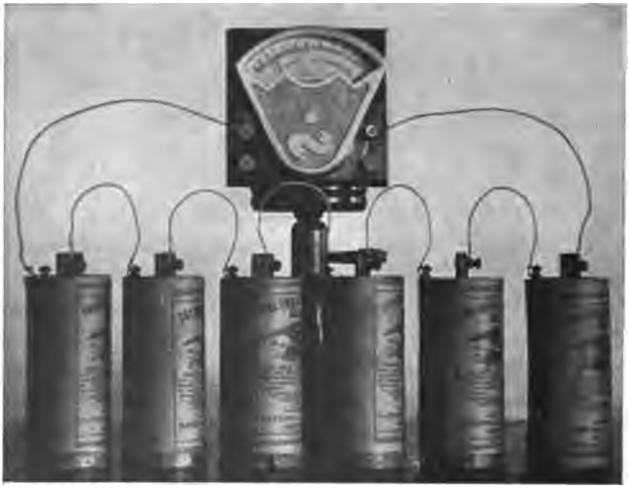
Cells may be grouped in one of three ways: (1) In *series;* (2) In *parallel;* (3) In *series-parallel.* The kind of arrangement which is best will depend on the kind of work which is to be done and the resistance which must be overcome.

369. Arrangement in Series.

A number of cells are said to be joined in series when the positive electrode of one is joined to the negative electrode of the next throughout the whole number of cells. The cells shown in Fig. 300 are joined in series.

By this arrangement *the E. M. F. is multiplied as many times as there are cells.* The E. M. F. of each cell shown in the figure is 1.3 volts. There are 6 cells in series, hence the E. M. F. is 7.8 volts. Each cell adds its pressure to that of the cells before it.

FIG. 300.



Cells in series.

At the same time the current must pass through each of the cells and, consequently, *the internal resistance will also be multiplied as many times as there are cells in series.*

The equation for Ohm's law (§ 365) becomes, for cells in series,

$$C = \frac{nE}{nr + R}$$

where n stands for the number of cells, r the internal resistance, and R the external resistance.

Suppose there are 8 cells in series, each having an E. M. F. of 2 volts and an internal resistance of .5 ohm, and it is desired to know the strength of the current which they will cause to flow through an external resistance of 6 ohms. By substitution,

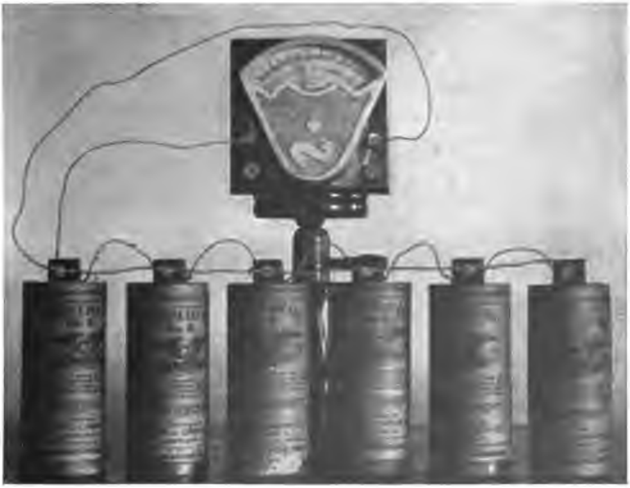
$$C = \frac{8 \times 2}{8 \times .5 + 6}$$

$$\therefore C = 1.6 \text{ amperes.}$$

370. Arrangement in Parallel.

A number of cells are said to be joined in parallel when all the positive electrodes are connected to one end of an external circuit and all the negative electrodes to the other end. In this case the E. M. F. is the same as that of a single cell, for each works independently of the others. Each causes a current of electricity to flow through the same external circuit.

FIG. 301.



Cells in parallel.

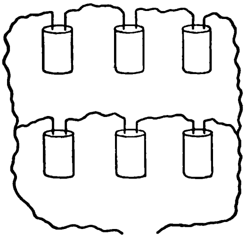
The internal resistance, however, ***has been decreased as many times as there are cells.*** This follows from the fact that when a number of cells are joined in this manner they, in fact, become one large cell, the area of whose plates are equal to the sum of the areas of the plates of the individual cells. Thus the area of the cross section of the liquid parallel to the plates has been increased as many times as there are cells. Hence the resistance is decreased in the same proportion.

The equation for cells in parallel is, then,

$$C = \frac{E}{\frac{r}{n} + R.}$$

Substitute values given at the end of the previous section and determine the strength of the current. It appears that this arrangement of cells is not desirable when a strong current is wanted, unless the external resistance is small. The internal resistance of a cell is a comparatively small quantity, and although it be divided by *n* the denominator of the fraction is not much reduced.

FIG. 302.



Cells in series-parallel.

371. Arrangement in Series-Parallel.

A number of cells are said to be joined in series-parallel when they are arranged in groups of the same number, the cells in each group being connected in series and the groups then joined in parallel. The six cells shown in Fig. 302 are arranged in two groups of three each. The cells in each group are in series, and the free electrodes of the same kind are then connected, putting the groups in parallel.

The equation for this arrangement is evidently a combination of the two preceding ones. Write the equation for the number of cells in series in any one of the groups and then divide the internal resistance by the number of groups in parallel. Thus,

$$C = \frac{N_s E}{\frac{N_s r}{N_g} + R},$$

where N_s stands for the number of cells in series in any one of the groups, and N_g stands for the number of groups.

Substitute values given at the end of § 369 and determine the strength of the current.

372. Best Arrangement of Cells.

The best arrangement for securing a current of maximum strength from any given number of cells is that by which the internal and external resistances are made as nearly equal as possible. It is evident, then, that when the external resistance is large the cells should be arranged in series, for thus the internal resistance is multiplied as many times as there are cells.

When the external resistance is small, it may be better to join the cells in parallel.

The series-parallel arrangement gives an opportunity to multiply or divide r in such a manner as to make it as nearly as possible equal to R.

Problems.

1. If a current of 6.2 amperes is flowing along a conductor whose resistance is 8.5 ohms, what is the E. M. F.? *Ans.* 52.7 volts.

2. If the current flowing through the filament of an incandescent lamp is .5 ampere and the electrical pressure is 100 volts, what is the resistance of the filament? *Ans.* 200 ohms.

3. What is the resistance of 400 feet of iron wire .01 inch in diameter? *Ans.* 252 ohms.

4. What is the resistance of a mile of copper wire No. 10? *Ans.* 5.25 ohms.

5. What will be the strength of the current from 12 Daniell's cells if $R = 50$ ohms and r of each cell $= .3$ ohms? Cells joined in series. *Ans.* .244 amperes.

6. How many dry cells will, when joined in series, send a current of .49 amperes through 300 feet of No. 20 copper wire? The internal resistance of each cell = 2 ohms. *Ans.* 4.

7. What is the maximum current from 12 cells, each having an E. M. F. = 2 volts and $r = 1$ ohm, when the external resistance is 4 ohms? *Ans.* 1.71 amperes.

8. A wire of a certain size and length has a resistance of 20 ohms. What is the resistance of another wire of the same kind whose diameter is twice as great and the length one-half as great? *Ans.* 2.5 ohms.

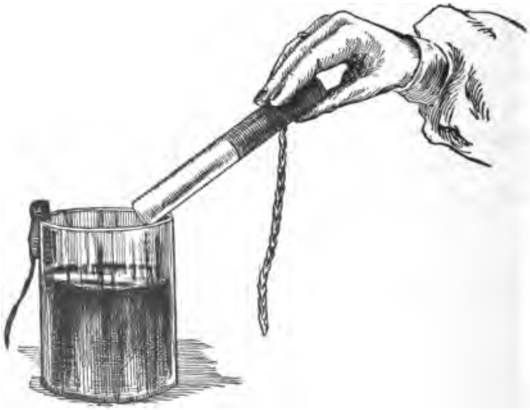
9. What length of German silver wire, No. 30, must be used to secure a resistance of 40 ohms? *Ans.* 29.63 ft.

10. An electric light wire No. 6 is found to have a resistance of .4 ohm per 1000 ft. If the line is 4 miles long, what is the total resistance? *Ans.* 8.45 ohms.

373. Electrolysis.

Electrolysis is a process in which oppositely charged ions are separated by means of an electric current. The principle has in fact been already explained in the description of the voltaic cell (§ 354).

FIG. 303.



Copper plating.

In electrolysis proper a current is passed through a solution in which there are free positive and negative ions, or the ions are joined loosely into molecules, the solution being in an unstable condition.

The solution is called the *electrolyte.*

The electrodes of a battery or other source of electricity are placed in the electrolyte. The positive electrode is called the *anode,* and the negative the cathode.

The positive ions are carried to the cathode and the negative ions to the anode.

If the solution is, for example, copper sulphate, the ions are Cu (copper, +) and SO_4 (sulphion, —). The copper will then be carried to and deposited upon the cathode where the potential is lower, and the SO_4 will be carried to the anode where it combines with H_2 of the water present, forming sulphuric acid and setting free the oxygen.

374. Electroplating.

Electroplating is accomplished by the electrolytic process just explained.

Some salt of the metal which is to be deposited on the cathode is dissolved in water, thus forming the electrolyte. The object to be plated is immersed in the electrolyte and connected to the negative electrode of a battery or dynamo. The object thus becomes the cathode. A plate of metal of the same kind as that dissolved in the electrolyte is also suspended in the solution a short distance from the cathode. This plate is connected to the positive electrode and constitutes the anode.

The metal ions are always carried in the direction the current is flowing and hence the plating is all on the cathode.

A variety of metals can be deposited in this manner, and electroplating is an important industry.

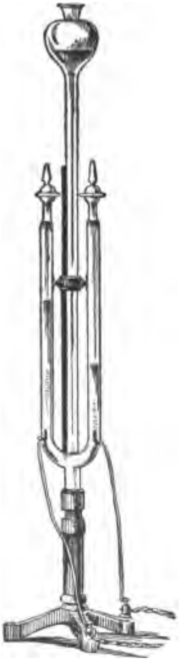
Plating by means of copper is a comparatively simple process and may easily be accomplished in the manner suggested in § 373.

374. Electrotyping.

Electrotyping is exactly the same in principle as electroplating. The metal employed is copper. The cathode is usually a plate of wax upon which the impression of the type has been made. This then is brushed over with graphite to make it a conductor. Copper will be deposited in an even layer over the surface of the wax, thus giving an exact reproduction of the type or other figure. The wax is then removed and the plate backed up with type metal and mounted on a block to make it type high.

This plate can be preserved and used from time to time, while the original type can be thrown into the cases and put to other use.

FIG. 304.



Electrolysis of water.

375a. Electrolysis of Water.

By use of an electric current water may be separated into the two gases of which it is composed—hydrogen and oxygen.

The apparatus shown in Fig. 304 is filled with water containing a small quantity of sulphuric acid. A platinum electrode is placed at the bottom of each of the graduated tubes.

If now the electrodes of a battery are connected to these platinum strips and a current of five or six volts is passed through the liquid, bubbles of gas will arise from each electrode and will displace the water in the tubes. The amount of gas evolved is shown by the volume of water displaced. It is observed that the volume of gas from one electrode is twice as great as that from the other.

Examination shows that this larger volume is hydrogen and the other oxygen.

The hydrogen is found to come from the negative electrode and the oxygen from the positive electrode.

This decomposition of the water is accomplished only indirectly. Pure water can not be electrolyzed. The action of the current is primarily upon the sulphuric acid (H_2SO_4). The H_2 of the H_2SO_4 is driven to the cathode, and the SO_4 is driven to the anode where it unites with an H_2 of the water (H_2O), forming a new molecule of sulphuric acid and setting the oxygen free.

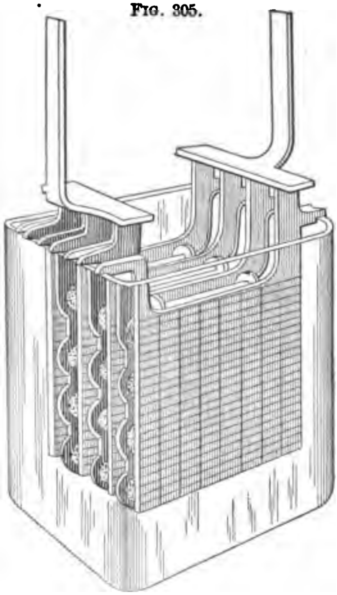
Thus the sulphuric acid is constantly replenished and the result is the same as if the water were decomposed directly.

376. Secondary, or Storage Cells.

A secondary cell is one in which the energy of an electric current may be stored and may at any time be converted into an electric current again.

The elements of this cell in its commonest form consist of lead plates moulded in the form of grids. The grids are filled with a paste of lead sulphate formed by mixing red lead or litharge with sulphuric acid.

FIG. 305.



Storage cell.

The electrolyte is dilute sulphuric acid. When a current is passed through the electrolyte from one lead plate to the other, hydrogen (H_2) is carried to the cathode, where it combines with the lead sulphate ($PbSO_4$), changing it to metallic lead and forming sulphuric acid in the liquid. This plate changes to a light gray color.

The SO_4 is carried to the other plate — the anode. Here it unites with the lead sulphate, forming an oxide of lead. This plate changes to a brown or plum color.

When the cell is charged, the plates may be distinguished by their color, the gray being negative and the brown positive. Thus the electric current has produced a difference in the chemical composition of the plates, and the energy in the cell consists in this difference and in the fact that when the plates are connected through an external circuit a current of electricity will flow and the plates will gradually become alike again.

In charging this cell the current must always be run in on the brown plates. In discharging, the current flows in the opposite direction, that is it comes from the brown plates into the external circuit.

This cell has an electromotive force of 2.1 volts when it is freshly charged. This gradually falls as the discharge continues. When it has reached 1.8 volts the cell should be recharged.

About 80 per cent of the energy used in storing the cell is returned in the discharge.

377. Units of Measurement.

Several electrical units have already been defined in section 353. These should now be reviewed along with the definitions here given.

The ampere is the unit by which the strength of a current is measured.

The legal definition of the ampere is the current which when passed through a proper solution of silver nitrate will deposit upon the cathode .001118 gram of silver in one second.

The strength measured in amperes is often called the amperage.

The ohm is the unit of electrical resistance. It is defined by law as the resistance offered to a current by a column of mercury 106. 3 cm. long, having a mass of 14.4521 g. and being at the temperature of melting ice.

The cross section of this column would be very nearly one square millimeter.

The volt is the unit employed in the measurement of electromotive force. It is that electromotive force which will cause a current of one ampere to flow through a resistance of one ohm.

The electromotive force expressed in volts is often called the voltage.

The coulomb is the unit employed in the measurement of the quantity of current. It is the quantity of current which passes any given section of a conductor in one second when the strength of the current is one ampere.

The watt is the unit of electrical power. It is the power possessed by a current of one ampere under a pressure of one volt. It may be defined in short as the volt-ampere. The power of any current, that is, the rate at which it will do work, may be found by multiplying the number of amperes by the number of volts. The product is the number of watts. There are 746 watts in one horse-power.

A kilowatt (K.W.) is 1000 watts.

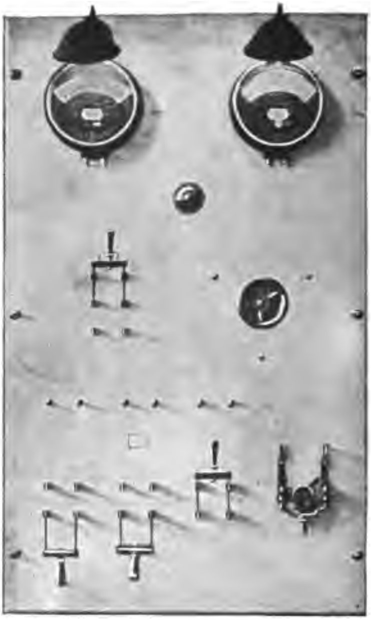
A watt-hour is a unit employed in the measurement of electrical work. It is the amount of energy expended in one hour when the current is one ampere and the pressure is one volt.

A kilowatt-hour is 1000 times a watt-hour.

378. Electrical Instruments.

Delicate and reliable measuring instruments are absolutely necessary not only for detecting the existence of a current but also for handling a current intelligently while it is at work. The instruments on the switchboard in an electrical plant are more necessary than the steam-gauge on a boiler. The investigator of electricity would be helpless without means of determining accurately the existence of very small currents, the amperage, the voltage, the properties of conductors and all the great variety of current effects.

FIG. 305A.



A switchboard.

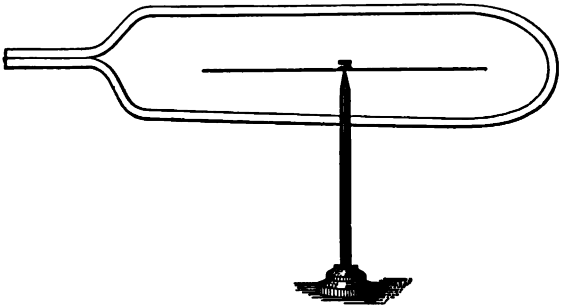
Progress in electrical science, as in other branches of science, depends largely upon the use of accurate and delicate measuring instruments.

379. Galvanoscope.

Any instrument used to determine the presence of a current in a conductor is a galvanoscope.

A simple form of galvanoscope is a magnetic needle within a loop of wire. The needle points north and south and lies in the vertical plane of the loop. When a current flows around the loop, the needle will be turned one way or the other, depending on the direction of the current. The fact that the needle turns, shows that a current is flowing.

FIG. 306.

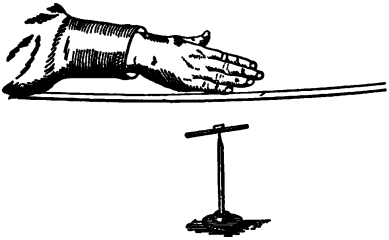


Simple galvanoscope.

380. Direction of the Current.

The fact that a magnetic needle is turned to one side or the other, depending on the direction in which the current flows, furnishes a means of determining the direction of the current.

FIG. 307.



Direction of the current.

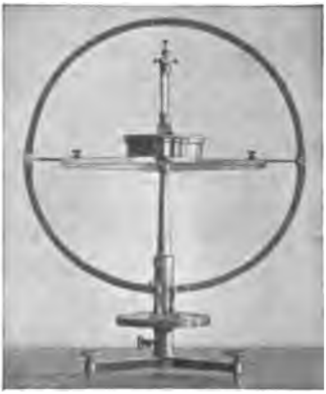
A common rule for this purpose is as follows:

Place the hand in such a position that the palm is upon the wire and facing the needle and so that the thumb is extended in *the direction the north-seeking end of the needle is deflected. The fingers will then point in the direction the current is flowing.*

381. Galvanometer.—Tangent.

If a galvanoscope is so constructed that the effect of a current can be accurately measured, it is then called a *galvanometer*. The instrument shown in Fig. 308 is a *tangent galvanometer*. Several coils of wire pass around the circular frame and end in the binding posts on the base.

FIG. 308.



Tangent galvanometer.

A small magnetic needle to which is attached a long aluminum pointer is mounted at the center of the circle. A circle beneath the pointer is graduated in degrees.

When a current is passed through the coils of wire the needle is deflected a certain number of degrees. If the current is made stronger, the needle will be deflected more. The strengths of currents, however, are not proportional to the angles through which they deflect the needle, but to the *tangents* of the angles.

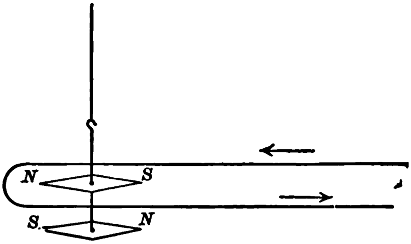
The strength of one current may then be compared to that of another by determining the deflection in each case and then comparing the tangents of these angles. If one of the currents is known to have a strength of one ampere, the amperage of the other can thus be found.

382. The Astatic Galvanometer.

A single magnetic needle will stand in the earth's magnetic meridian and so will point north and south. If the needle be disturbed it will return to this position because it is under the influence of the earth's magnetism.

If the needle is deflected by passing a current above or below it (§ 379), the force due to the current and that due to the magnetism of the earth are opposed to each other. If the current is very weak, it may not be able to cause any deflection of the needle. If, however, two similar needles are rigidly fastened to the same axis, as shown in Fig. 309, and the poles be pointed in opposite directions, the turning effect of the earth's magnetism is avoided. While the earth would turn one needle in one direction it would at the same time turn the other needle in the opposite direction. If the needles are exactly alike they will take any position and will act like an unmagnetized piece of steel.

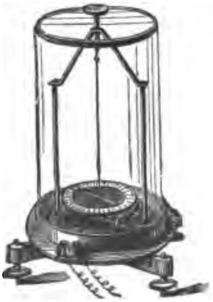
Fig. 309.



Astatic needle.

By making the needles slightly different in length or in strength of magnetism, the turning effect of the earth's magnetism may be made more or less as desired. Such a needle is *astatic*, that is, does not take a *stand* in the earth's magnetic meridian.

Fig. 310.



Astatic galvanometer.

If a current of electricity is passed along a conductor above the upper needle and returned between the two needles, show by the law of direction (§ 380) that both needles will be deflected in the same direction.

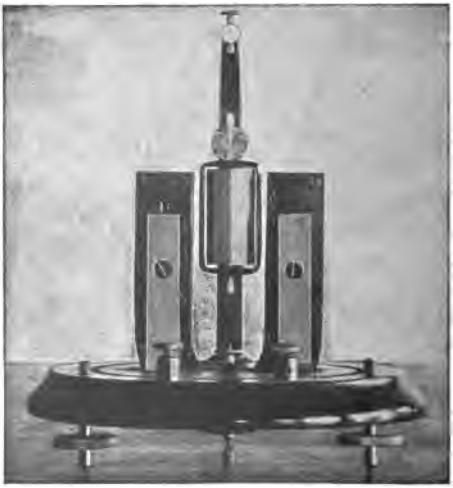
Pass the current between the two needles and return it below the lower needle. Show that the deflection will be in the opposite direction.

By passing the current several times around the needle, the effect is multiplied as many times as there are turns of wire. The needle may be supported by a fine silk fiber, as shown in Fig. 310. This is a very delicate galvanometer.

383. The D'Arsonval Galvanometer.

The D'Arsonval galvanometer consists of a coil of many turns of fine wire suspended in a strong magnetic field. The field is produced by a strong horse-shoe magnet. The

FIG. 311.



D'Arsonval galvanometer.

coil is suspended by a very flexible wire of phosphor-bronze. The same kind of wire, in form of a spiral, connects the other end of the coil below.

The coil turns and tends to set itself at right angles to the plane of the magnet whenever a current is passed through it. In this galvanometer, then, the magnet is stationary and the coil movable, while, in the other forms described, the coil is stationary and the magnet movable.

A small circular mirror is attached to the coil and reflects the graduations of a horizontal scale placed in front of it.

The slight torsion of the suspension wire is sufficient to restore the coil to its first position when the current ceases to flow.

This is the best galvanometer for most purposes. It can be made exceedingly delicate and is not appreciably affected by outside currents, magnets, or magnetic material as is the astatic galvanometer.

Another great advantage of the D'Arsonval is that it is "dead-beat." That is, the coil will promptly turn to a certain position and come to rest without vibrating back and forth a long time as in the case of the astatic.

384. Coulomb-Meter.

The *coulomb-meter*, commonly called the *voltameter*, is an instrument by which the quantity of electricity is measured. It is simply an electrolytic cell through which a current is passed from anode to cathode. Two common forms are the copper and silver voltameters. Their operation depends upon a law of electrolysis, that *the mass of metal deposited by a current upon the cathode is proportional to the quantity of the current.*

The apparatus illustrated in section 373 may is used as a coulomb-meter. If a solution of copper sulphate is used as the electrolyte, then both the anode and the cathode should be plates of copper.

The cathode is weighed, then placed in the solution and the current allowed to flow for a certain time, say one-half hour. The cathode is then removed and weighed again. The difference in weight is the mass of copper deposited by the current.

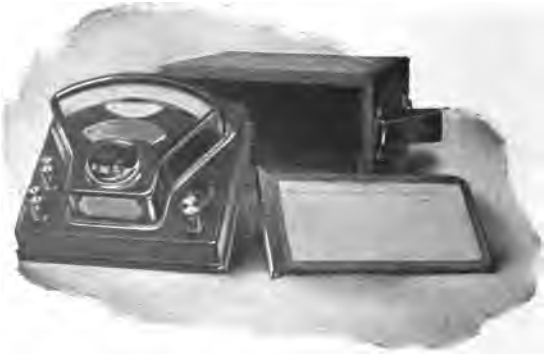
The mass of copper deposited by one coulomb of electricity is .000329 g. This is called the *electrochemical equivalent* of copper. If the weight of copper deposited be divided by .000329, the quotient will be the number of *coulombs.*

The strength of the current in amperes may then be found by dividing the number of coulombs by the time in seconds during which the current was flowing.

385. The Ampere-Meter.

The *ampere-meter*, or *ammeter*, is an instrument by which the strength of the current in amperes is indicated by a pointer which moves over a graduated dial.

FIG. 312.



Ammeter.

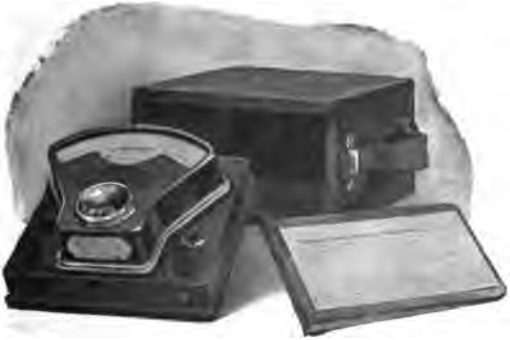
The principle of a common form of ammeter is exactly the same as that of the D'Arsonval galvanometer (§ 383). A strong horse-shoe magnet furnishes the magnetic field. In this field is mounted a coil similar to that of the D'Arsonval. The coil turns freely on pivots and is held in place by coiled springs similar to the hair-spring of a watch.

A part of the current passes through the coil, thus causing the pointer attached to it to move over the scale. These instruments are portable and can be made to indicate the strength of the current with great accuracy.

386. The Voltmeter.

A voltmeter is an instrument by which the electrical pressure in volts may be determined. These, like ammeters, are made in a variety of forms, but the best are those which are constructed on the same principle as that of the ammeter described above. A large resistance is introduced in the circuit which passes through the moving coil, and the current in this circuit will then be in proportion to the electrical pressure. The hand attached to the moveable coil will move in response to any change of pressure. The scale is so graduated that the pressure is read directly in volts.

FIG. 313.



Voltmeter.

387. Measure of Resistance.

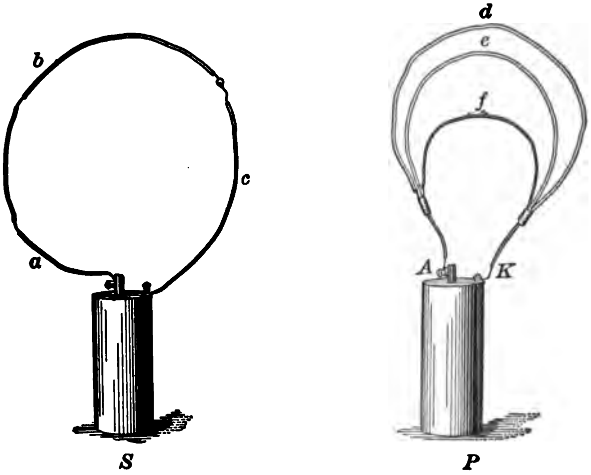
Methods of calculating the resistance of conductors have already been described in section 366. It is desirable, however, to be able to determine the resistance of a wire, a system of wires, or any kind of an electrical circuit, by use of proper measuring instruments.

The resistance in an electrical circuit may depend on many conditions, such as the kind of material used, the temperature, the kind of joints where wires are connected, and so on.

388. Circuits in Series and in Parallel.

Wires may be arranged in series or in parallel, just as in the case of cells (§ 369).

FIG. 314.



Series and parallel circuits.

In Fig. 314 *S*, the wires *a*, *b*, and *c* are connected in ***series***. The whole current must pass through each wire.

In Fig. 314 *P*, the wires are connected in *parallel*. The current will divide at the connector above *A* or *K*, part flowing through each of the circuits *d*, *e*, and *f*.

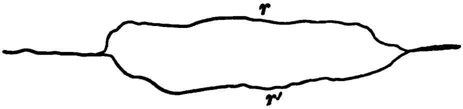
389. Resistance in Series and Parallel Circuits.

When conductors are connected in series, the resistance is the sum of the resistances of the individual conductors.

In parallel circuits it is evident that the resistance is decreased by increasing the number of conductors. It is the same as increasing the size of a conductor.

The ability of a wire to conduct electricity between two points of different potential is called conductivity. This is the inverse of resistance. If the conductivity of one wire is three times as great as that of another, its resistance is one-third as great. The conductivity is, then, the reciprocal of the resistance. If the resistance is R, the conductivity is $\frac{1}{R}$.

FIG. 315.



Divided circuit.

Now, the conductivity of any number of conductors in parallel is the sum of their respective conductivities. If, then, r and r', Fig. 315, represent the respective resistance of two conductors in parallel, and R their combined resistance,

$$\frac{1}{R} = \frac{1}{r} + \frac{1}{r'}$$

$$\therefore R = \frac{rr'}{r + r'}$$

Therefore *the resistance of two conductors in parallel is equal to the product of their respective resistances divided by their sum.*

The combined resistance of any number of conductors in parallel may be found by use of the equation

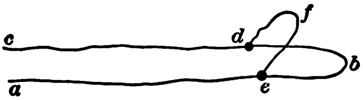
$$\frac{1}{R} = \frac{1}{r} + \frac{1}{r'} + \frac{1}{r''} \text{ etc.}$$

390. Shunts.

A shunt is an additional path through which electricity may flow.

Thus, if the main conductor is *abc*, Fig. 316, then the added conductor *dfe* is a shunt, or, *aefdc* may be considered the main circuit, and *ebd* would then be the shunt.

FIG. 316.

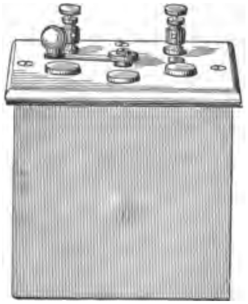


A shunt.

Whenever a shunt is used the current will be divided between two conductors, the quantity of current flowing through each being *inversely as their resistances.*

If the resistance of *ebd*, for example, is 9 ohms, and that of the shunt 1 ohm, then $\frac{9}{10}$ of the current will flow through the shunt and $\frac{1}{10}$ through *ebd.*

FIG. 317.



A shunt box.

Shunts having a known relation to galvanometers or other instruments are inclosed in boxes, as illustrated in Fig. 317.

By use of a proper shunt a delicate instrument may be used to measure a strong current.

Suppose the shunt is such that only $\frac{1}{100}$ of the current flows through a delicate ammeter. Then if the ammeter indicates $\frac{5}{100}$ of an ampere, the total current must be 5 amperes.

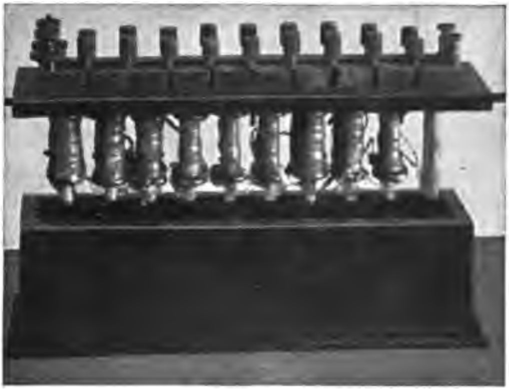
391. A Rheostat.

A rheostat is a known resistance which may be inserted into any circuit to check the flow of the current.

Rheostats usually consist of a number of resistance coils put up in a box and arranged so that the resistance may be adjusted to suit the conditions at hand.

In Fig. 318 is shown a common form of rheostat where resistance is introduced by removing plugs. While the plugs are in place, the current passes through them and the heavy brass on the top of the box with practically no resistance. But when a plug is removed, the current is forced to pass down through one of the resistance coils.

FIG. 318.



Rheostat lifted from the box.

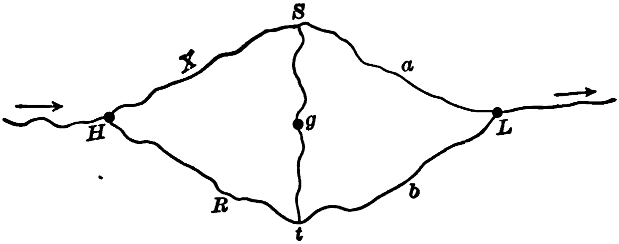
392. The Wheatstone Bridge.

The Wheatstone bridge is an electrical instrument used for a variety of useful purposes. The use here described is that of measuring resistance of conductors.

The principle of the instrument is that when a current divides and flows along two branches, as *HSL* and *HtL*, Fig. 319, points may be found, one on each branch, such that there is no difference of potential between them. If these two points, *S* and *t*, say, are then connected by a conductor, no current will flow from one to the other. A delicate galvanometer introduced at *g* will not be affected.

It is found that this condition exists whenever the resistance of *X* is to the resistance of *R* as that of *a* is to that of *b*. *X* stands for the resistance of *HS*; *R*, *Ht*, ; *a*, *SL*; and *b*, *tL*.

FIG. 319.



Principles of the Wheatstone bridge.

Expressed in the common form of a proportion,

$$X : R = a : b$$

when no current flows between *s* and *t*.

When any three of these terms are known, the fourth may easily be found.

The bridge is constructed in a manner similar to that shown in Fig. 320. Heavy brass bars form the sides of the squares. Gaps in each of the four arms permit the introduction of resistances. *X* is the conductor whose resistance is to be determined. *R* is a rheostat (§ 391), *a* and *b* are small resistance coils which may be introduced by the removal of plugs. A galvanometer is introduced as shown.

The current enters at *H*, say, divides itself between the two branches of the bridge, and passes out at *L*.

To find the resistance of *X* by a first trial, make the resistance at *a* and *b* equal. Then adjust the resistance in the rheostat until the galvanometer needle shows no deflection while the current flows from *H* to *L*. Then

$$\begin{aligned} X : R &= a : b \\ \text{but } a &= b \\ \therefore X &= R. \end{aligned}$$

The number of ohms in *R* can be read on the cover of the resistance box. *X* has the same resistance.

More exact determination of the resistance of *X* can usually be made when the resistances in *a* and *b* are not equal.

FIG. 320.

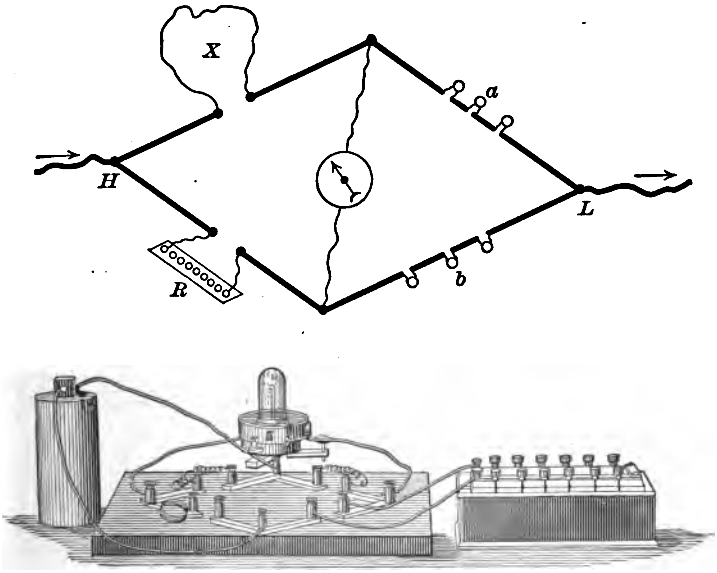


Diagram and photograph of Wheatstone bridge.

Suppose the 10-ohm coil is put into circuit in the arm *b*, and the 1-ohm coil in the arm *a*. Then the proportion becomes,

$$X : R = 1 : 10$$

$$\therefore X = \frac{R}{10}.$$

The instrument is operated just as before, but the reading on the resistance box must now be divided by 10 to get the resistance of *X*. Suppose the reading on the box is 16 ohms. Then the resistance of *X* is 1.6 ohms.

393. The Slide Wire Bridge.

The principle of the slide wire bridge is exactly the same as that of the Wheatstone bridge. The construction is slightly different. As shown in Fig. 321, *SS'* is a German-silver wire stretched upon a meter stick between two binding posts. A sliding contact piece rests over this wire and may be moved back and forth between *S* and *S'*. The segments of the German-silver wire on each side of the contact piece correspond to the arms *a* and *b* of the Wheatstone bridge. A wire with a galvanometer in circuit connects the slide to a post between *R* and *X*. Battery electrodes are joined to *B* and *B'*. The operation of finding the resistance is the same as in the Wheatstone bridge.

FIG. 321.

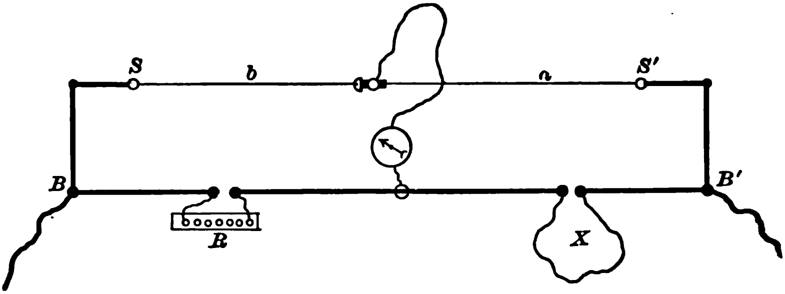


Diagram of the slide wire bridge.

The resistance of a conductor is proportional to its length, so that the lengths of *a* and *b* have the same ratio as their resistances.

If the lengths *a* and *b* are equal, then *X* equals *R* when no current flows through the galvanometer.

By moving the slide, a point may readily be found where no current flows through the galvanometer. Then

$$X : R = a : b$$

from which *X* may be readily calculated.

394. Heat Produced by a Current.

When a current passes over a wire, some of its energy is converted into heat. If the wire is large and is a good conductor, the heat may not be perceptible. When the wire is a poor conductor and the electrical pressure is sufficient to force a strong current through it, intense heat may be developed.

The amount of heat due to a current of electricity is proportional to *the resistance of the conductor*, *the time during which the current flows*, *and the square of the strength of the current.*

The quantity of heat in calories may be calculated by use of the equation,

$$H = .24C^2Rt,$$

where H is the number of calories; C, amperes; R, ohms; and t, seconds.

From Ohm's law (§ 365), $R = \frac{E}{C}$. Substituting this value of R in the equation above,

$$H = .24CEt.$$

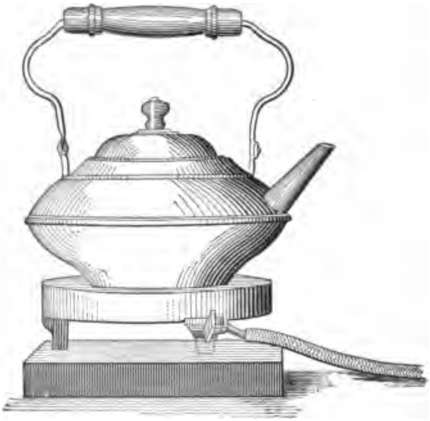
The product CE equals the number of watts (§ 377), consequently the quantity of heat is equal to the number of watts multiplied by the time and the factor .24.

395. Use of Heat from Electric Current.

In the transmission of electricity from place to place, it is very desirable that none of the energy be expended in heating the conductor. Hence copper wires of the proper size must be used. In wiring a building for electric lights, the insurance rules require that the wires be of a certain size and that they be put up in a certain manner. Otherwise they will not insure a building against fire.

It is often desirable, however, to use the electric current for the purpose of producing heat. The carbons of the arc and incandescent lamps are intensely heated that they may produce light. Coils of German-silver wire or other high resistance wire are heated by the passage of a current through them. In this manner the electric stove is made.

FIG. 322.



Electric stove.

Soldering-coppers, smoothing-irons, and baking-ovens are heated in a similar manner.

396. Effect of Heat on Conductivity.

Heat decreases the conductivity of most substances. In case of metals, the conductivity decreases and the resistance increases as the temperature rises.

In case of carbon, the change is in the opposite direction. The resistance of a carbon filament in an incandescent lamp when hot is about one-half as great as when it is cold.

Problems.

1. What is the power of a current whose strength is 23 amperes and the pressure 150 volts? *Ans.* 3.45 K. W.

2. The power of a certain dynamo is 3 K. W. The current which it produces is under a pressure of 120 volts. What strength of current may it produce? *Ans.* 25 amperes.

3. A current of one ampere deflects the needle of a certain tangent galvanometer 45°. What is the strength of a second current which causes a deflection of 57°? (Tan. 45° = 1. Tan. 57° = 1.54.) *Ans.* 1.54 amperes.

4. If a certain current when passed through a copper sulphate solution for 30 minutes causes a deposit of 6.58 g. of copper upon the cathode, what is the quantity and strength of the current? *Ans.* 20,000 coulombs, 11.11 amperes.

5. Four wires whose individual resistances are 4, 12, 8.5, and 3.2 ohms are connected end to end to form an electric circuit. What is the resistance of the circuit? *Ans.* 27.7 ohms.

6. Two wires whose respective resistances are 6 and 8 ohms are connected in parallel. What is their combined resistance? *Ans.* 3.43 ohms.

7. Three wires in parallel have separate resistances, 3, 6, and 8 ohms. Find their combined resistance. *Ans.* 1.6 ohms.

8. How much of a current will flow through a shunt when its resistance is $\frac{1}{99}$ of that of the other branch of a circuit. *Ans.* $\frac{99}{10}$.

9. If the arm *a* of the Wheatstone bridge contains 20 ohms resistance, and the arm *b*, 4 ohms, what is the resistance of X when the reading of R is 15 ohms and no current flows through the galvanometer? *Ans.* 75 ohms.

10. If the resistance wire of a slide wire bridge is one meter long and the arm *a* is 40 cm. long, what is the resistance of X when R is 30 ohms? *Ans.* 20 ohms.

11. How much heat will be generated in 20 minutes by a current whose strength is 12 amperes, the resistance of the conductor being 20 ohms? *Ans.* 829,440 calories.

12. What must be the electrical power that 48 calories of heat may be generated per second? *Ans.* 200 watts.

397. Magnetic Field Produced by a Current.

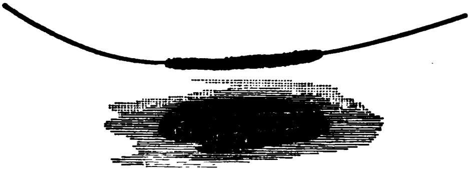
When an electric current flows along a conductor, it affects not only the conductor but also the region around it.

A conductor in some way makes a path along which electricity will flow, but it is not known whether electricity travels on the conductor or on the ether through which the conductor passes.

However this may be, it is found that the conductor is surrounded by a field which has magnetic properties.

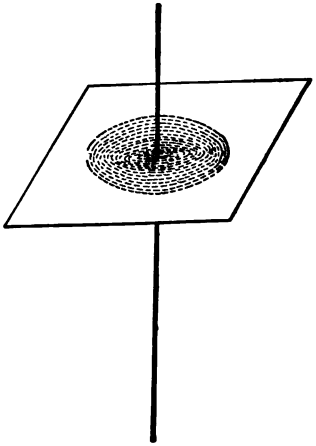
If a copper wire through which a current of several amperes is flowing be held in iron filings, as shown in Fig. 323, a bunch of the filings will cling to the wire. When the circuit is broken the filings will fall from the wire.

FIG. 323.



Effect of electric current on iron filings.

FIG. 324.



Lines of force around a wire.

If the wire is passed vertically through a hole in the center of a stiff card, Fig. 324, and filings are sprinkled upon the card while the current flows, the filings will arrange themselves in concentric circles about the wire.

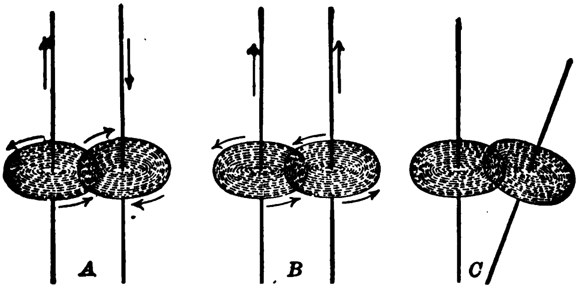
Such experiments show that the field about a conducting wire is a very important part of an electrical current.

These concentric lines of force are always present around a conductor whenever a current is flowing. Their direction is assumed to be such that if the wire is grasped with the right hand, the thumb pointing in the direction the current flows, the fingers will point in the direction of the lines of force.

398. Action of Currents on Each Other.

When two or more currents are flowing near to each other, each being surrounded by its lines of force, the currents and their conductors will move in such a manner as to make as many lines of force as possible move in the same direction. In Fig. 325, *A*, the overlapping lines of force are those which would be produced by two currents flowing in opposite directions. The more they overlap, the greater is the number of lines in opposite directions, consequently these currents will repel each other to make as many lines as possible move in the same direction.

FIG. 325.



Effect of currents on each other.

In *B* it is seen that the more nearly the fields coincide, the greater the number of lines in the same direction. Hence these currents will attract each other.

In *C*, where one current is at an angle to the other, it will be necessary for the currents to become parallel and flow as in *B*, that the greatest number of lines of force may be in the same direction.

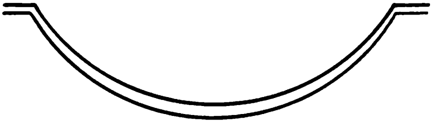
Experiment 71.

The action described above may be easily illustrated by passing a current through two strands of copper wire which are suspended as shown in Fig. 326.

The wire should be covered with a cotton or silk insulation. The size should be about No. 24. By first stretching the wire it can be made to hang in a regular curve. Their distance apart should not be more than about one centimeter. The ends may be fastened to screws or, better, to binding posts.

A large primary battery or, better, a storage cell, should be used to furnish the current. First, make the connections so that the current will flow out on one wire and back on the other. They will be repelled from each other because the currents are flowing in opposite directions. (See Fig. 325, *A*).

FIG. 326.



To show the effect of currents in the same or opposite directions.

Now make connections so that the current will flow through both wires in the same direction. The wires will attract each other and will cling together as long as the current flows. (See Fig. 325, *B*.)

The mutual action of currents may be stated in three laws:

(1) *Parallel currents in opposite directions repel each other.*

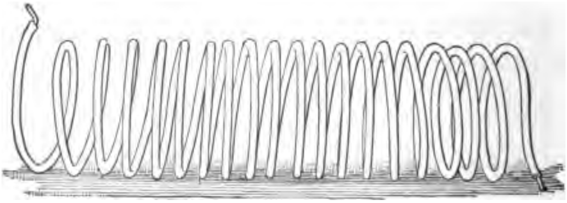
(2) *Parallel currents in the same direction attract each other.*

(3) *Currents flowing at an angle to each other tend to become parallel and flow in the same direction.*

399. The Solenoid, or Helix.

A solenoid is a hollow cylinder formed by a number of turns of insulated wire side by side (Fig. 327).

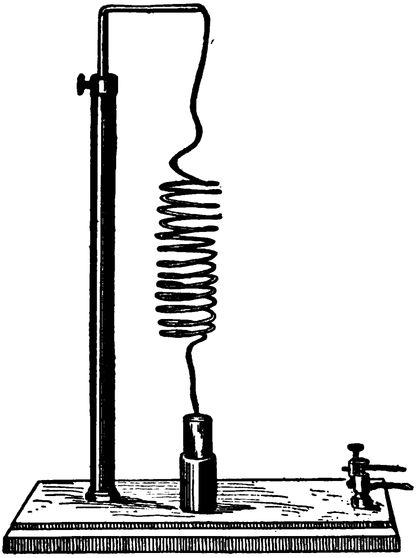
FIG. 327.



A solenoid.

The current flows in the same direction in each turn of the solenoid, and so each part of the wire is attracted by adjacent parts above and below it. This may be shown by the simple apparatus illustrated in Fig. 328, where one end of a solenoid is supported and the other end dips into a cup of mercury. When the solenoid and mercury are put in circuit with a battery, the attraction of the adjacent coils shortens the solenoid and breaks the circuit. Again the circuit is made and then broken. This continues while the current flows.

FIG. 328.



Parallel currents attracted to each other.

400. Poles of a Solenoid.

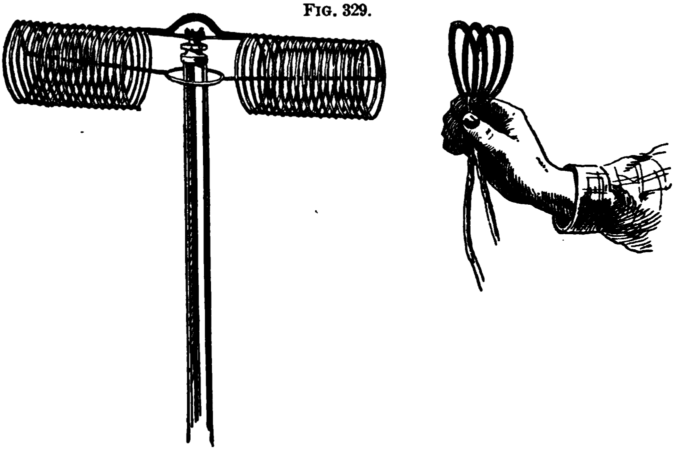
The attraction and repulsion between two solenoids is the same as that between two magnets. Solenoids have north-seeking and south-seeking poles, just as magnets have.

The poles may be determined in the following manner .

Place the palm of the right hand upon the solenoid in such a way that the fingers point in the direction the current flows. The outstretched thumb will then point towards the north-seeking pole.

When two solenoids through which currents are passing are brought near to each other, they behave just as two magnets would. Their like poles repel and their unlike poles attract one another. If the poles of a magnet be brought near to a solenoid the effect is the same as that between two magnets, or between two solenoids.

Fig. 329.



Action of one solenoid on another.

401. The Electromagnet.

The electromagnet is a solenoid containing a core of soft iron or steel.

When a current is passed through the solenoid, the core becomes a magnet.

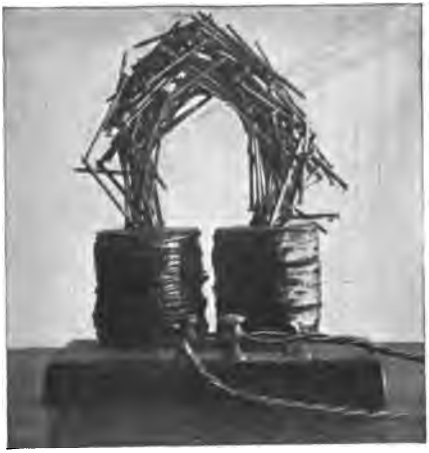
To explain this effect it is assumed that each molecule of the iron has a current of electricity circulating in or around it. According to the third law stated in section 398, all these small currents tend to become parallel and flow in the same direction under the influence of the large current flowing around the core. This is known as Ampere's theory of magnetism.

Since the like poles of the molecules are thus all turned in the same direction, one end of the core must be positive and the other end negative.

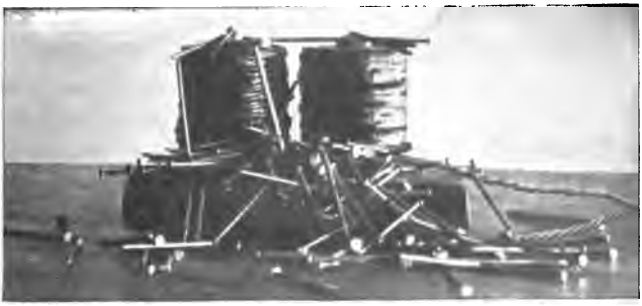
402. Strength of an Electromagnet.

The strength of any given electromagnet varies directly as the strength of the current and the number of turns in the solenoid.

FIG. 330.



The electromagnet—while the current flows.



The electromagnet—when the current is broken.

A current of one ampere passing once around is called one *ampere-turn*. We may then say that the strength of an electromagnet varies directly as the number of ampere-turns.

This is true, however, only within certain limits. A point is reached where an increase of the current will not increase the magnetism. The iron is then said to be saturated. This condition, according to the theory, has been reached when all the molecules have been completely turned.

Hard steel may be used as a core in an electromagnet, but it cannot be very strongly magnetized and it does not lose its magnetism when the current ceases to flow. Soft steel is better. Soft iron is best.

Soft Swedish iron can be very strongly magnetized and, when the current ceases, very little magnetism is found in the iron.

403. Use of Electromagnets.

The most useful applications of electricity are made by means of electromagnets with soft iron cores.

The magnetic field of all large dynamos and motors is made by means of electromagnets.

The communication of intelligence by telegraphy is directly dependent on the electromagnet.

The ringing of electric gongs and the numerous ways by which electric signals are given would not be possible without electromagnets.

In some large shops a powerful electromagnet is attached to the traveling crane and used to transport from place to place masses of iron which weigh several tons.

In many other ways the electromagnet is of the greatest service.

404. Telegraphy.

Telegraphy is a process of transmitting messages from place to place by means of an electric current.

The principal instruments employed in this process are a *battery, a transmitting key*, a *sounder*, a *relay*, and *electric conductors* connecting the various instruments.

The principle underlying the operation is that a piece of soft iron becomes a magnet while a current flows around it, but at once loses its magnetism when the current ceases. This change in the soft iron core can easily be made to produce a series of intelligible signals. Since the current may be made to pass over many miles of a line wire before it reaches the electromagnet, telegraphy is an efficient means of sending messages over long distances.

FIG. 331.

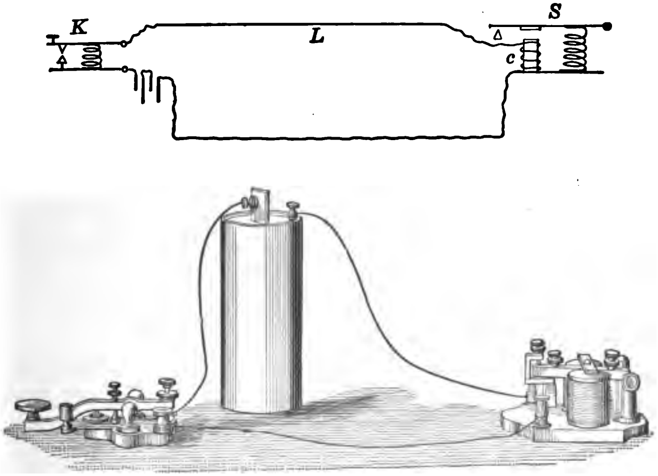


Diagram and photograph of a key and sounder.

In its simplest form a telegraph outfit consists of a *key*, a *battery*, a *sounder*, and a *line* connecting all in series. These are shown by diagram and photograph in Fig. 331. When an operator at K presses upon the key, the battery circuit is closed. The current then flows over the line L, which may be many miles long, and passes many times around the soft iron core at *c*, then back to the battery either through the ground or a return wire. Above *c* is a bar of soft iron, called the armature, which is drawn down whenever a current flows, and is raised by a spring when the current ceases to flow. The stroke of the armature when it is pulled down by the electromagnet produces a sound which is understood by the operator at that end of the line.

FIG. 332.

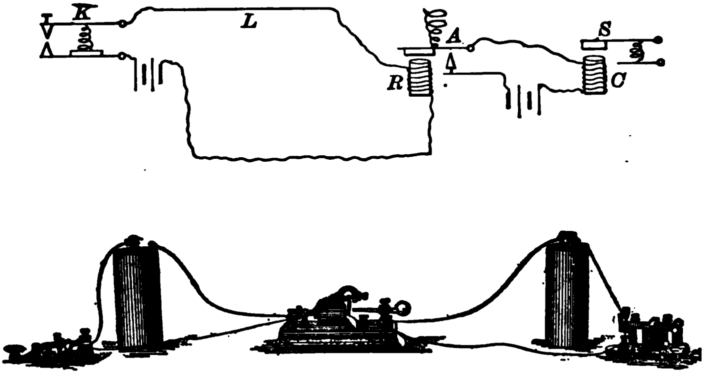


Diagram and photograph of a key, relay and sounder.

The sounds thus produced consist of a series of dots, dashes, and spaces which constitute the telegraphic alphabet and by means of which words may be spelled out.

When the distance is very great, the resistance of the line is such that the current becomes very weak and cannot operate the sounder. In that case a relay is used.

A relay is an instrument which can be operated by a very weak current and which is used only to close the circuit of another battery.

As shown in Fig. 332, the current which passes over a long line *L* may be very weak, and yet strong enough to attract the armature *A*, thus closing the circuit of a fresh battery which then operates the sounder *S*.

Of course there must be a key and a sounder at each of end of the line so that each operator may either send or receive a message. The diagram in Fig. 333 shows the instruments and the connections for a complete telegraph outfit.

FIG. 333.

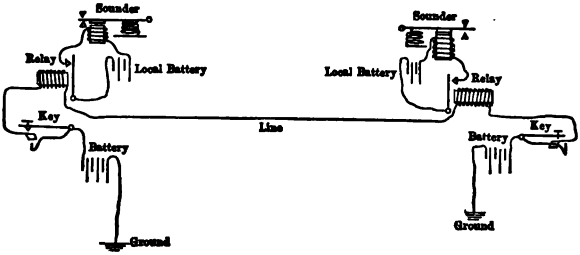


Diagram showing the essential parts of a telegraph system.

405. The Electric Bell.

The electric bell is operated by an electromagnet. The construction is such that the armature automatically makes and breaks the current which produces the magnetism.

The bell is shown by diagram and photograph in Fig. 334. The current must be made to flow through the *coils of the electromagnet* and the *contact screw*, *S*. The student should make drawings of this circuit until he is familiar with it.

When the armature is drawn to the magnet, the hammer strikes the gong. At the same time the circuit is broken at *S*. A spring then throws the armature back and renews the contact. Again the armature is attracted, and a rapid repetition of this operation causes a continuous ringing of the bell as long as the current flows.

FIG. 334.

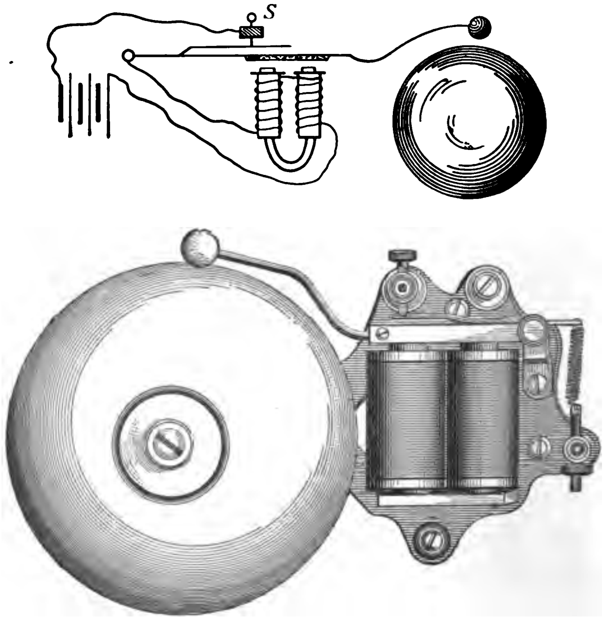


Diagram and photograph of the electric bell.

By means of an electric button at some point in a circuit, the current may be made to flow through the electromagnet of the bell whenever desired.

406. Induction.

Induction, in a general sense, as the term is used in physics, may be defined as the influence which a magnet, an electrified body, or an electric current has upon surrounding bodies without having any apparent contact with them.

Three kinds of induction may be mentioned : (1) *Magnetic.* This has been discussed in § 317. (2) *Electrostatic.* This has been described in § 329. (3) *Electromagnetic.* This is now to be described.

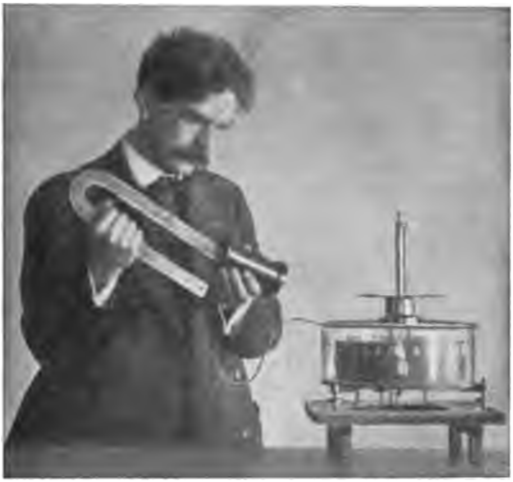
407. Current induced by a Magnet.

If a coil of many turns of fine wire is connected to a delicate galvanometer, and a magnet is thrust into it, the galvanometer coil or needle will be deflected. This shows that a current is thus set up in the coil.

If the magnet is allowed to remain at rest within the coil, the coil of the galvanometer will swing back to its first position, showing that the current has ceased to flow.

By suddenly withdrawing the magnet from the coil, a current will again flow, but in an opposite direction, as indicated by the deflection in the galvanometer to the other side.

FIG. 335.



Current induced by thrusting a magnet into a coil.

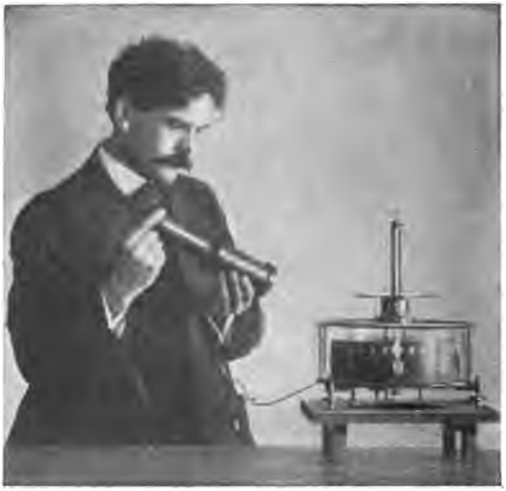
The same operations may be repeated with the other pole of the magnet. Similar currents will be induced, but in directions opposite to those obtained when the first pole was used.

It appears from this experiment that a current is induced only while the magnet is in motion, and that opposite motions of the same pole produce currents in opposite directions.

408. Current induced by Another Current.

When a coil of wire is used in place of the magnet, very similar results will be obtained. This is as we would expect, for, as explained in § 400, solenoids exhibit the same properties as magnets. The approach of the coil or solenoid induces a current in one direction, and when it is withdrawn the current is in an opposite direction.

Fig. 336.



Current induced by thrusting one coil into another.

If a soft iron core is placed in the coil the induced current is stronger.

409. Cause of the Induced Current.

We have already learned that a magnet or an electric current is surrounded by a magnetic field which may be mapped out by lines called lines of force. The stronger the magnet or the current, the greater the number of lines of force.

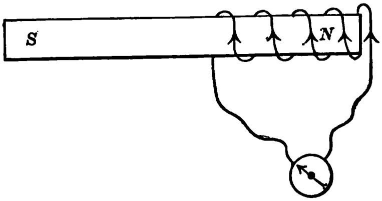
When a coil or any closed circuit is in a magnetic field then if, in any manner, the number of lines of force within the coil be increased or diminished, a current will be induced. It is the *changing* field which causes the current. No current is induced in a conductor which is at *rest* in a magnetic field.

This change in the number of lines of force may be effected in a variety of ways. A magnet may be thrust into a coil or drawn from it. The magnet may be at rest and the coil be moved to or from it. Similarly for two coils. One coil may be at rest within another and if the circuit through one of them is made and broken, the magnetic field will be thus changed and a current will be induced in the other. If a current in one coil rapidly changes the direction in which it flows, as is the case in the *alternating current*, a current will be induced in an adjacent conductor.

410. Direction of the Induced Current.

It is found that when the north-seeking pole of a magnet is thrust into a closed circuit, as shown in Fig. 337, the current will flow in the direction shown by the arrow-heads.

FIG. 337.

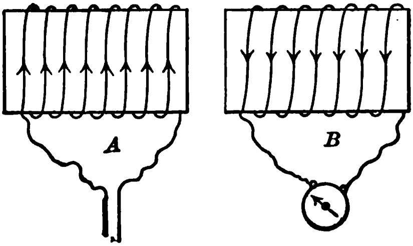


Direction of induced current.

Thus the end of the solenoid to which the north-seeking end of the magnet is approached, becomes also a pole of the same kind (§ 400), and like poles repel each other.

When the magnet is withdrawn, the current will flow in the opposite direction. Thus the end of the solenoid from which the north-seeking pole of the magnet is withdrawn, becomes a south-seeking pole, and unlike poles attract each other.

FIG. 338.



Lenz's law.

Thus in each case the induced current has opposed the motion which has produced it.

The same is found to be the case where one current is induced by another.

Let *A* and *B* be two solenoids.

Pass a current through *A* in the direction shown by arrow-heads. Approach it to *B*, and a current will be induced in the direction indicated. Thus two like poles are brought together. When *A* is withdrawn, the current in *B* will be reversed. Thus unlike poles are separated.

These facts are stated concisely in Lenz's law, as follows: *The direction of the induced current is always such that its magnetic field opposes the motion which produces it.*

411. Source of the Induced Current.

It has been shown (§ 409) that a current is induced only when there is a change in the number of lines of force. This change can be brought about only by *changes* in the strength of the inducing current or by a relative motion of a magnet and a coil. Energy is required to produce these changes in motion or strength.

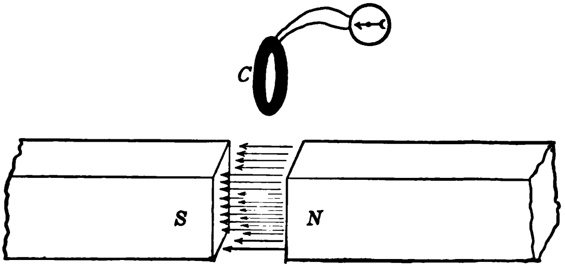
It is also shown (§410) that an induced current always produces a magnetic field which opposes the motion producing it. Energy must be expended in overcoming this resistance.

The real source of the induced current is, then, some form of energy which has been expended. The energy then appears in the induced current. This is no exception to the general principle of conservation of energy.

412. Electromotive Force of an Induced Current.

If a conductor, *C*, Fig 339, is moved through the magnetic field so as to *cut across* the lines of force, a current will be induced in the conductor. The electromotive force will be proportional to the *rate* at which the conductor cuts lines of force. When the conductor moves *along* the lines of force, no current is generated.

FIG. 339.



Cutting lines of force.

By making the conductor in the form of a coil of many turns of insulated copper wire, the electromotive force of each turn is added to that produced by the other turns. This is like an arrangement of cells in series and the electromotive force of one turn is multiplied as many times as there are turns.

413. Laws of Electromagnetic Induction.

(1) *Any* CHANGE *in the number of lines of force passing through a closed conducting circuit, induces a current in that circuit.*

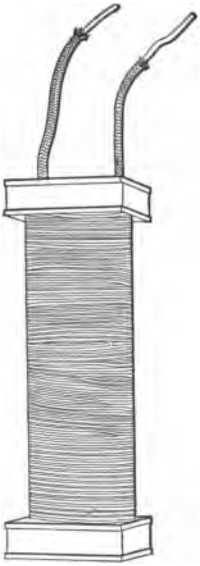
(2) *The direction of the induced current is always such that its magnetic field opposes the motion which produces it* (Lenz's law).

(3) *The electromotive force of the induced current is directly proportional to the* RATE *at which the number of lines of force are increased or decreased, or, the* RATE *at which the lines of force are cut.*

414. Self-Induction.

A single strand of insulated copper wire wrapped many times around a soft iron core is called a *spark coil*, a *kicking coil*, or a *choke coil*, depending on the use to which it is put. The principle in all is the same. If the circuit is broken while a current is flowing through such a coil, a bright spark is produced at the gap. The spark is very much stronger than when the coil is not in the circuit.

Fig. 340.



A spark coil.

What is the source of this extra current?

The principles of induction will furnish an explanation. The turns on the coil are lying side by side, so that the current in each tends to induce a current in the others near by.

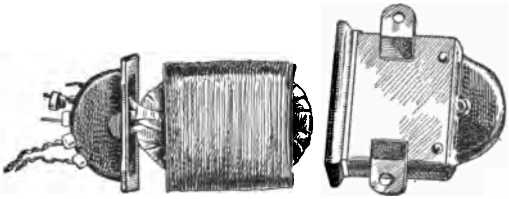
When the current is first started it induces a current in the opposite direction (§ 410). On this account it requires a short time for the current from the battery to attain full strength. When, however, the circuit is broken, a current is induced in the same direction as the battery current. It is both the induced current and the battery current which then leaps across the gap where a circuit is broken.

This property which a current possesses of resisting any attempt to change its motion is often called *electromagnetic* *inertia.* The spark coil is in common use for the purpose of lighting gas jets, igniting a mixture of gases in a gas engine, and other purposes of this character.

415. Transformers.

A transformer is a device by which the voltage and amperage of a current may be changed without changing the amount of energy. The change is effected by electromagnetic induction. Of course, then, only those currents which are started and stopped or increased and decreased in rapid succession, or those in which the direction of the current is changed many times in a second, can be transformed.

FIG. 341.



Transformer with iron case removed.

In structure the transformer consists of two coils of wire side by side with a soft iron core or with sheets of soft iron packed in and around the coils. The coils have no metallic connection. The first coil, that through which the current flows, is called the *primary.* The second coil, that into which the current is induced, is called the *secondary.*

Transformers are of two kinds—*step-up* and *step-down.* The step-up transformer increases the voltage and decreases the amperage. The step-down produces the opposite effect.

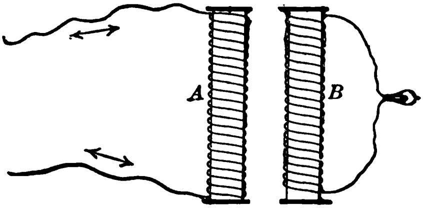
The change depends on the relative number of turns of wire in the primary and secondary coils. If, for example, there are 100 turns in the primary and 1000 turns in the secondary, the voltage will be increased 10 times and the amperage decreased 10 times. This is then a step-up transformer.

If there are the same number of turns in both coils, the current will not be changed.

416. Power of the Transformed Current.

Since whenever the transformer increases or decreases the voltage, it decreases or increases the amperage, the number of watts—*CE* (§ 377)—will be a constant quantity. Suppose there is a current of 100 volts and 10 amperes flowing through the primary. The power is then 1000 watts. If the transformer raises the pressure to 500 volts, the strength of the current will fall to 2 amperes, but the power of the current is still 1000 watts.

Fig. 342.



Alternating current passed through coil *A* will cause a glow of the lamp in coil *B*.

A good transformer gives out nearly all the energy that is put into it. A small percentage is lost in heat.

417. Use of the Transformer.

The chief use of the transformer is in the safe and economical distribution of the *alternating current* now so commonly used for light and power. This is the kind of current which frequently changes its direction, surging back and forth many times in a second. The alternating current, therefore, can be transformed by induction.

Now, it is known that a comparatively small copper wire will carry a great deal of electrical energy when the pressure is great and the strength of the current is small. As was shown in section 394, the heat developed by a current varies directly as the square of the current's strength. So, by making the pressure great and the strength small, the same energy may be transmitted with less loss on the wire.

An alternating current of 1500 volts or more is generated by an *alternator* at the electric light plant, and this current is distributed by copper wires to points where it is to be used. But it would not be safe to bring such a current into a building. It would be liable to start a fire and it would cause the death of any one who would come into proper contact with it.

Transformers are placed outside the buildings, on the walls or upon telephone posts near by. Here the pressure is reduced to a safe voltage and the secondary coil only is distributed through the building. This is one important use of step-down transformers.

In transmitting energy over a considerable distance as, for example, from Niagara Falls to Buffalo, the current is first passed through a step-up transformer where its pressure may be raised to 30,000 or more volts. At the other end of the line this current passes through a step-down transformer and is then used for light and power.

Thus the expense of heavy copper wires which would be needed for a current of the same number of watts at low pressure is avoided.

418. The Induction Coil.

The induction coil is a step-up transformer with but few turns of wire in the primary and a great number of turns in the secondary coil.

The usual construction is shown by the diagram, Fig. 343.

A constant current is ordinarily used to operate the coil, and the circuit is rapidly made and broken by an arrangement exactly like that used in the electric bell (§ 405). The circuit must pass through the primary coil and the point of contact *S*. The circuit of the primary current is shown by the arrows. A piece of soft iron, *i*, is attached to the end of a spring and located in front of the soft iron core. The movement the current flows, the magnetism of the core attracts *i* and breaks the circuit at *S*. The magnetism then ceases

FIG. 343.

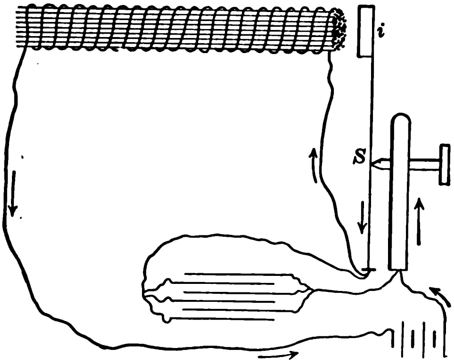
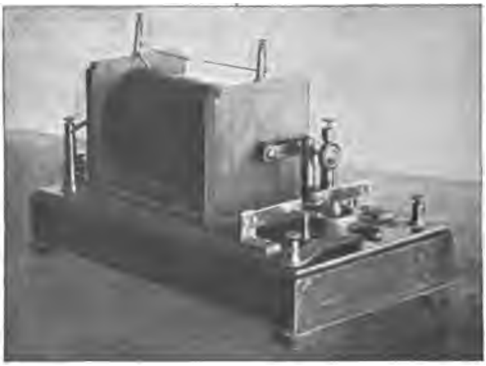


Diagram showing the connections in the induction coil. Secondary coil omitted.

FIG. 344.



Induction coil.

and the spring restores the contact at *S*. This operation is rapidly repeated.

A condenser is attached to the opposite sides of the point where the circuit is broken. This is a necessary part of a good induction coil. The primary coil with its iron core acts as a spark coil (§ 414). The extra current, instead of leaping across the gap at *S* where the circuit is broken, will be stored in the condenser. Before another contact is made at *S*, the condenser is discharged through the primary coil and the battery in a direction opposite to that of the battery current, thus demagnetizing the core.

The condenser thus causes a sudden change in the number of lines of force both by causing a sharp break at *S* and by demagnetizing the core. Since the induced electromotive force is proportional to the rate of change of lines of force (§ 412), it is seen that the condenser performs an important part.

The primary coil must be separated from the secondary by a heavy tube of hard rubber or some other good insulating material.

Coils of this kind are made with as much as 250 miles of fine copper wire in the secondary, but probably not more than that number of feet of coarse wire in the primary coil. Thus the "step-up" is enormous and will cause a difference of potential at the terminals of the secondary sufficient to cause a spark 30 to 40 inches long through the air.

419. The Telephone.

A telephone is a device by which an electric current is made to reproduce sound. Attention was first called to this means of communication in 1876 A. D. Since that time it has become world-wide in its use and is an essential factor in modern industrial life.

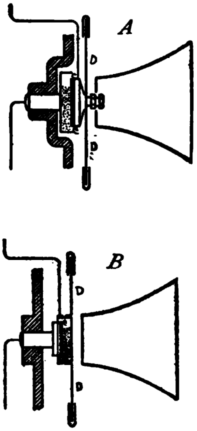
The essential parts of a telephone system are a *transmitter*, a *line*, and a *receiver*.

420. The Transmitter.

The transmitter is a device in which the sound waves cause a variation in a local current passing through the primary of a small induction coil.

The structure of two forms of a transmitter is shown in Fig. 345.

FIG. 345.



Telephone transmitter.

At the bottom of the mouthpiece is a thin metallic disk, *D*. In the form shown at *A*, the metal disk is in contact with a carbon disk, *c*. Back of the carbon is a brass cup which is loosely filled with granules of hard carbon.

In the form shown at *B*, the granules lie next to the diaphragm and the carbon disk is back of them.

The carbon forms part of the battery circuit, and its use is explained below.

421. The Microphone.—Purpose of the Carbon.

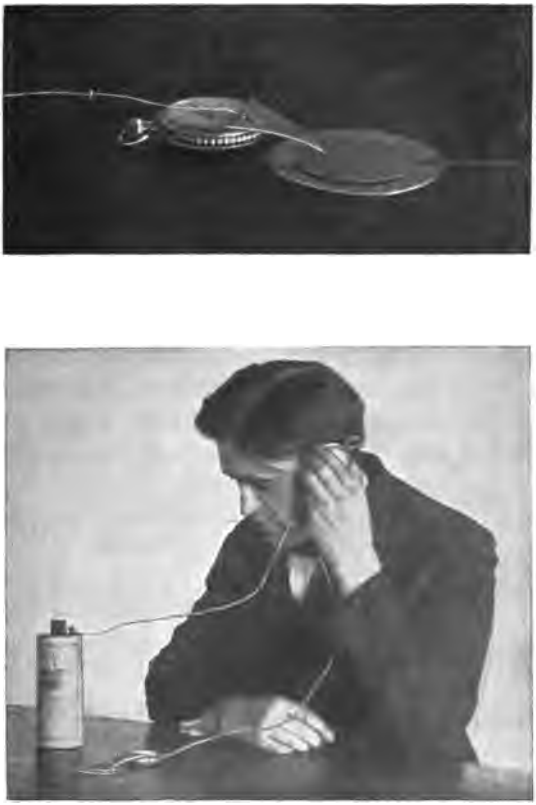
When carbon forms part of an electric circuit, it is found that its conductivity varies with change of pressure upon it. Even the slight vibrations of the metal disk caused by waves of sound will cause a change in the conductivity of the carbon and thus produce a pulsating current through a small induction coil whose primary is also in the battery circuit. This produces an induced current which is sent out over the line.

The carbon acts as a *microphone*,—that is, as a means of magnifying the effect of small disturbances. This will be understood from the following experiment:

Experiment 72.

Solder a wire to a circular piece of brass or tin and connect to one pole of a dry cell. Place the brass flat upon the table and lay upon it a thin disk or small granule of carbon. Solder another wire to a small triangular piece of brass and connect to one post of a telephone receiver. Complete the circuit to the cell. Now place a watch upon the table near the carbon. Lay the triangular piece of brass upon it so that one corner will project over and just touch the carbon. If the receiver be then pressed to the ear, the ticking of the watch will sound even louder than when the watch itself is pressed to the ear.

FIG. 346.

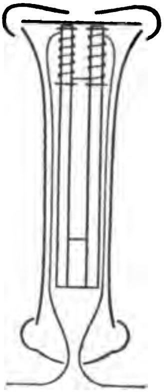


The microphone.

422. The Receiver.

The telephone receiver, as shown in Fig. 347, consists of a permanent magnet, a bobbin of fine wire, and an iron disk. The current sent over the line passes through the wire of the bobbin, varying the force of the magnet upon the metal disk. Thus the disk of the receiver is made to vibrate back and forth in accordance with variations in the current caused by the vibration of the metal disk in the transmitter.

FIG. 347.

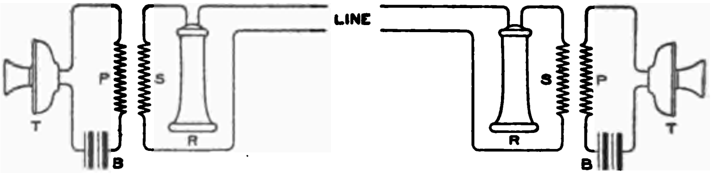


Telephone receiver.

423. Operation of the Telephone.

A transmitter and a receiver are placed at each end of the line and the circuit is completed as shown in Fig. 348. The ground may be used for the "return," but a complete "metallic" circuit is better. When a receiver is taken down, the local battery flows continuously through the carbons and the primary coil. This circuit is only a few feet in length and does not leave the box in which the battery is located.

FIG. 348.



Complete telephone outfit. T, transmitter. B, battery. P, primary of induction coil. S, secondary of induction coil. R, receiver.

When the current is varied by talking near the disk, a current is induced in the secondary of the coil. This current, now "stepped-up" to a high pressure, passes over the line through the secondary coil and the receiver at the other station, back along the return line, and through the home receiver to the other terminal of the secondary from which it started.

424. The Dynamo.

A dynamo is a machine designed to convert mechanical energy into electrical energy. The steam engine, for example, does work on a dynamo, and the dynamo produces an electric current. This current contains all the energy that was received from the engine except about 10 per cent. which was lost in heat and friction.

There are two kinds of dynamos—*alternators* and *constant-current dynamos.*

There are three essential parts of a dynamo: (1) *The field magnets;* (2) *The armature;* (3) *The collecting brushes.*

The magnets are nearly always of the horse-shoe form. They create a strong magnetic field between the two poles—that is, a field in which there are many lines of force.

FIG. 349.

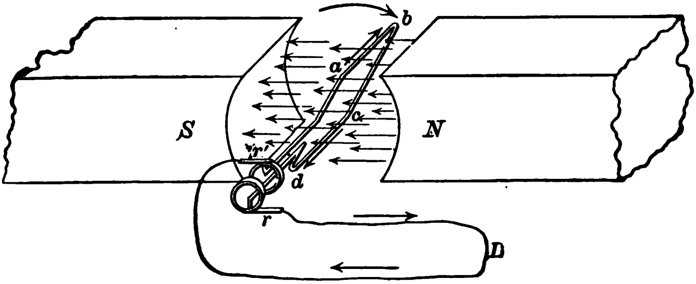


Diagram showing essential parts of a dynamo.

In all large dynamos electromagnets are used. In small ones the magnets may be permanent. In the latter case the machine is called a *magneto.*

The armature consists of coils of wire wrapped around a soft iron core. This is mounted so as to rotate in the magnetic field and cut lines of force. The current is thus generated in the manner described in section 412.

The essential parts of a dynamo are shown in diagram in Fig. 349. The north-seeking pole of the field magnet is marked *N*. The south-seeking pole, *S*. The armature is here a single loop of wire, *abcd*. The ends of the loop are connected to rings upon which rest the collecting brushes *r* and *r′*.

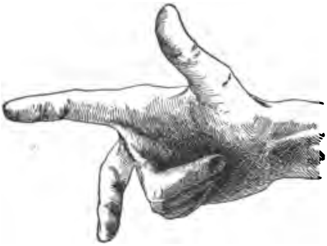
When the loop is rotated, it cuts the lines of force, causing a current to flow out to the brushes and through the external circuit.

425. Direction of the Current.

A rule commonly used to determine the direction of the current in the armature is as follows:

Extend the thumb, first finger, and middle finger of the right hand in such a manner that each will be at right angles to the other two. Place the hand in such a position that the first finger will point in the direction of the lines of force (N to S), and the thumb in the direction in which the conductor moves. The middle finger will then point in the direction in which the current flows. The side *ab* of the loop is represented as moving downward across the lines of force. The direction of the current will then be as represented by the arrows.

FIG. 350.



To determine the direction of the current.

The student should assume the loop to be in various positions and should apply the rule in each case.

426. The Alternator.

An alternator is a dynamo which produces an alternating current.

How this is done will be understood by a further study of the diagram in Fig. 349.

Let the coil be rotated as indicated by the curved arrow above it. While the side *ab* is moving downward in front of the pole *N*, *dc* will be moving upward in front of the pole *S*. An application of the law for direction shows that the currents thus induced by cutting lines of force will flow in opposite directions in relation to each other, but in the same direction *around* the coil. This continues as long as *ab* and *cd* are moving in the same direction across the lines of force—that is, during one-half of one complete rotation. Then, as the rotation continues, the sides of the coil cut the lines in an opposite direction and the current is completely reversed. Each time the coil is turned half way around, the direction of the current is changed.

Each end of the coil is attached to a ring. The rings are attached to the axis of the coil and rotate with it.

Brushes *r* and *r'* slide upon the rings and conduct the current out upon the line *L*. The line current is thus changed in direction twice during each complete rotation of the coil or armature.

Each change in direction is called an *alternation*.

Two alternations constitute a *cycle*—that is, a circle or series of changes which will be repeated in the next cycle.

The time required for one cycle is the *period*.

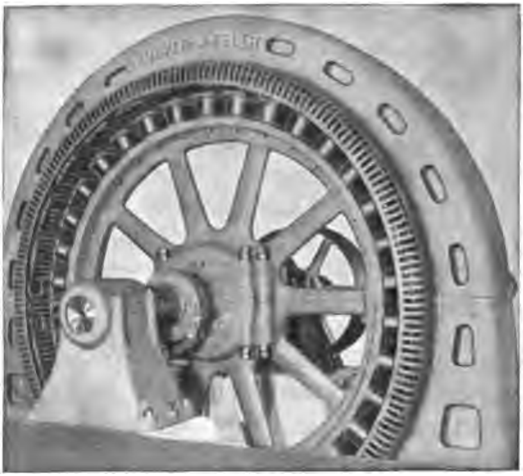
The number of cycles in one second is the *frequency*. The frequency is one-half the number of alternations in one second.

427. Form of Modern Alternators.

In modern forms of alternators the frequency is seldom more than 60 nor less than 25 cycles per second. To produce 60 cycles in a second with a machine like that shown in Fig. 349, the armature would have to make 3600 rotations in one minute.

To avoid such high speed, a number of pole pieces are arranged in a circle around the armature, making what is called a multipolar machine (Fig. 351). These poles are wound so that north and south-seeking poles alternate in position. A cycle is then produced in the circuit by the passage of any two adjacent poles. If there are ten poles, there are five cycles during one rotation of the armature.

FIG. 351.



The alternating generator.

428. Constant-Current Dynamo.

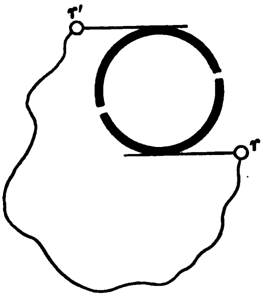
All dynamos produce an alternating current. This current, however, may be commuted or changed to a *constant current*—one which flows in the same direction all the time. This is done by a simple attachment called the *commutator*.

The operation of the commutator may be readily understood from Fig. 352. It is a tube, split into halves. The two parts are insulated from each other and connected one to each terminal of the coil of the armature. It is rigidly fastened to the axis of the armature.

The brushes *r* and *r′* are so placed that they glide from one side to the other of the commutator at the same moment that the current is reversed in the armature.

Thus the current flows constantly in the same direction through the external circuit, though it continues as an alternating current in the armature.

FIG. 352.



The commutator.

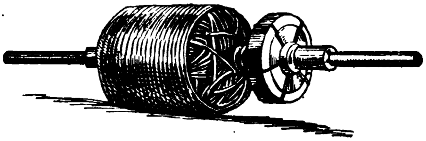
When the armature consists of only one coil of a number of turns of wire, the two segments of the commutator are sufficient. But this arrangement, while it produces a current in one direction through the external circuit, does not produce a steady current. The current pulsates, being alternately strong and weak. While the wire of the coil is cutting directly across the lines of force the current is strong. While it moves parallel to the lines the current is zero. For most purposes this kind of current is not desirable.

The current is made nearly steady by use of an armature and commutator, explained in the next section.

429. The Armature.

The drum armature is illustrated in Fig. 353. It consists of a core built up with disks of sheet iron.

FIG. 353.



The drum armature.

Coils of wire consisting of a number of turns are wrapped from end to end around the core. There are as many segments in the commutator as there are coils on the armature.

The ends of each coil are attached to adjacent segments of the commutator in such a manner as to connect all the coils in series.

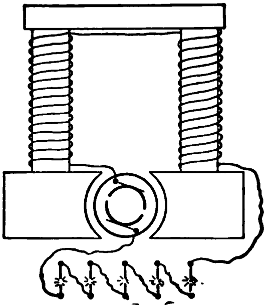
By this arrangement a current of nearly constant strength is produced, for although each coil operates as though it were alone, there are a sufficient number of them so that in each successive instant one of them will come into position where it produces its strongest current.

If the core were solid iron, currents would be set up within the iron itself. These would result in heat and a loss of energy. The sheet iron disks prevent this.

430. The Field Magnets.

Electromagnets are used to produce the field in all large dynamos and motors. The soft iron core may be wound with insulated copper wire in one of three ways: (1) Series; (2) Parallel; (3) Compound.

FIG. 354.



Dynamo wound in series.

In the *series winding* the coils of the armature and those of the field are connected in series, as shown in Fig. 354. The entire current flows through both the field and the armature coils. The stronger the current, the greater the number of ampere turns on the field magnets (§ 402). Thus the current will be made still stronger. If a large resistance be inserted in the external circuit, the current will be weakened and the field will also be weakened.

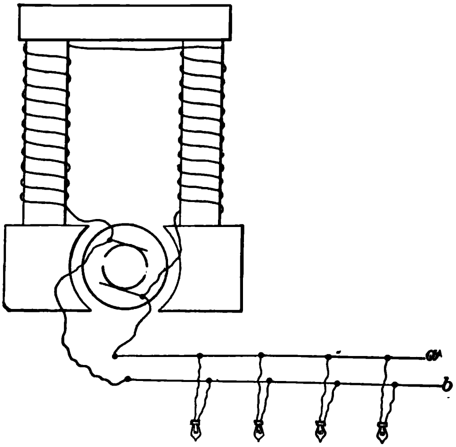
This kind of winding, then, is desirable only when the "load" on the external circuit is nearly constant, as, for example, a series of arc lamps.

In the *parallel winding*, also called the *shunt winding*, there are a large number of turns of wire on the field magnets.

The current generated in the armature divides at the brushes, part flowing around the field magnets and part through the external circuit. The field winding is a shunt to the external circuit.

When added resistance is thrown into the external circuit, more current will thus be forced into the shunt and a stronger field is produced. This will cause greater pressure and the current will be kept at nearly uniform pressure although the amperage in the external circuit may be frequently changed.

FIG. 355.

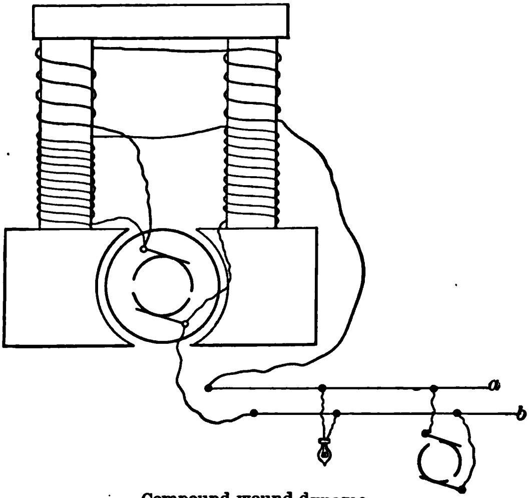


Shunt-wound dynamo.

Dynamos wound in this manner are in common use for incandescent lighting.

In the *compound winding* both the series and the shunt winding are used on the same dynamo, as shown in Fig. 356. The series coil has few turns of heavy wire while the shunt has many turns of finer wire. The coils are wrapped in the same direction. The advantage of both the series and the shunt are combined in this machine and the pressure is automatically kept constant.

FIG. 356.



Compound-wound dynamo.

431. Electric Motors.

The principles of electric motors are very much like those of dynamos.

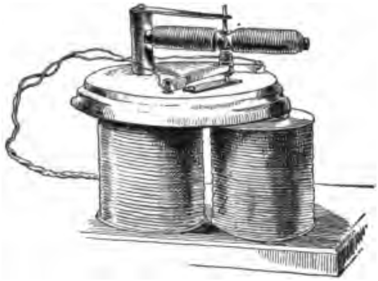
The action of the motor is the reverse of that of the dynamo. While the dynamo converts mechanical into electrical energy, the motor converts electrical into mechanical energy. A good direct-current dynamo is a good motor and is often sold for both purposes.

The action of a motor in its simplest form may be illustrated by the apparatus shown in Fig. 357.

A bar electromagnet is mounted so that it may freely rotate. The iron core is wrapped with a continuous wire from end to end, the terminals being connected to the two segments of a commutator at the bottom of the vertical shaft. This is the armature. A current may be passed through the coil by connecting a battery to the brushes which rub against the segments of the commutator. Each time the segments of the commutator change brushes, the polarity of the armature will change.

If this is now placed in a magnetic field, the armature will rapidly rotate in accordance with the laws of attraction and repulsion of magnets and currents.

FIG. 357.



Illustrating the principle of the electric motor.

Alternating-current motors are also in common use, but their construction differs from that of constant-current motors.

432. Electric Light.

Lighting by use of the electric current has become a very common practice since the invention of the dynamo.

Numerous lamps have been invented by which the electric current can be made to produce light, but the two most in use are the *incandescent lamp* and the *arc lamp.*

433. Incandescent Lamp.

The incandescent lamp, with which everyone is familiar, consists of a glass bulb in which is mounted a filament of carbon (§ 396). The air is then pumped out and the bulb sealed.

A current of sufficient pressure and strength will make the filament white hot—that is, incandescent. The carbon is not consumed because there is no oxygen within the bulb to combine with it.

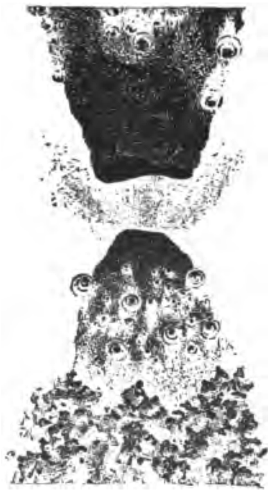
A 16 c.p. lamp requires a current of about one-half ampere when the pressure is about 100 volts.

Incandescent lamps are, as a rule, connected in *parallel.* The main circuit is open at *ab*, Fig. 355, and the current flows from one side to the other through the lamps only. The greater the number of lamps inserted in this manner, the less the resistance and the greater the flow of current.

434. The Arc Lamp.

When two sticks of carbon are placed in contact end to end, a current of electricity may be passed through them without producing any heat. If, while a current of sufficient strength and pressure is flowing, the carbons are separated a short distance, some carbon will be vaporized, forming an arc upon which the current will continue to flow between the terminals.

FIG. 358.



Points of the arc-light carbons.

The intense heat of the arc and carbon terminals causes what is called the arc light.

After the current has been flowing for a time, if a constant current (not alternating) is used, a depression called the crater is found at the end of the positive carbon, while the negative terminal is pointed as shown in Fig. 358. The crater is the point of most intense light. In lamps which hang in stores and streets, the positive carbon is above so that the light from the crater may be radiated downward.

The carbons are kept at the proper distance apart by a clutch which holds the upper carbon. The clutch is operated automatically by the current itself. When the carbons come close together, the resistance of the arc is less. When farther apart, greater. In proportion as this resistance changes, the upper carbon is raised or lowered.

In the ordinary arc lamp a current of 9 or 10 amperes is used. The pressure for each lamp is about 50 volts. The electric power for each lamp would then be about 500 watts, or ten times that of one 16 c.p. incandescent.

Arc lamps are joined in series, as shown in Fig. 354. The current completes its circuit by flowing through each lamp in the series.

If there are 40 lamps in series and the difference of potential of the carbons in each is 50 volts, then the voltage at the dynamo is 2000.

CHAPTER XVI.

RADIATIONS.

435. Nature and Kinds of Radiations.

Radiation, in a general sense, refers to that which passes out in every direction from a point which is the source and cause of the radiation.

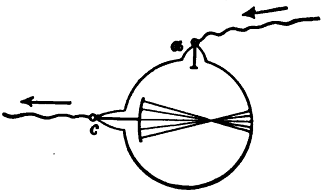
In this sense, sound may be said to radiate from a vibrating body.

The term radiation, in science, however, has come to be applied more strictly to heat waves, light waves, and electric waves, any of which are set up by proper disturbances in the ether. The ether is the medium by which the energy is transmitted in the form of waves.

Another kind of radiation consists of small particles of a material substance projected with great velocity. Such, for example, as the emanations from radium or other substance of a similar character.

436. Cathode Rays.

FIG. 359.



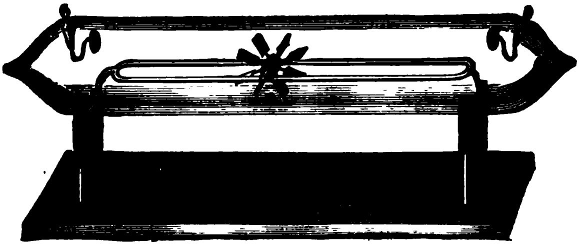
A form of Crookes' tube.

A Crookes' tube is a glass bulb from which the air is nearly all exhausted. Electrodes *a* and *c*, Fig 359, are sealed into the glass at two points of the tube. When a current of high voltage from an induction coil or an electric machine is passed through the tube, certain rays are emitted from the cathode *c*. These are called the *cathode rays*. They are emitted in directions perpendicular to the surface of the cathode. They cause the glass to phosphoresce at points where they strike it. They are deflected from their course when a magnet is held to one side of the tube. They probably consist of very small particles, not larger than $\frac{1}{1000}$ of a hydrogen atom, charged with negative electricity. These particles will pass readily through light substances such as wood, paper, and aluminum.

437. Effects of Cathode Rays.

When cathode rays are made to fall upon a wheel with vanes, as shown in Fig. 360, the wheel will rotate in one direction when the rays fall upon the vanes above the axis, and in the opposite direction when the rays fall upon the vanes below the axis.

FIG. 360.



Wheel propelled by cathode rays.

Another noticeable effect is the intense heat produced when the cathode rays are focused upon any body within the tube.

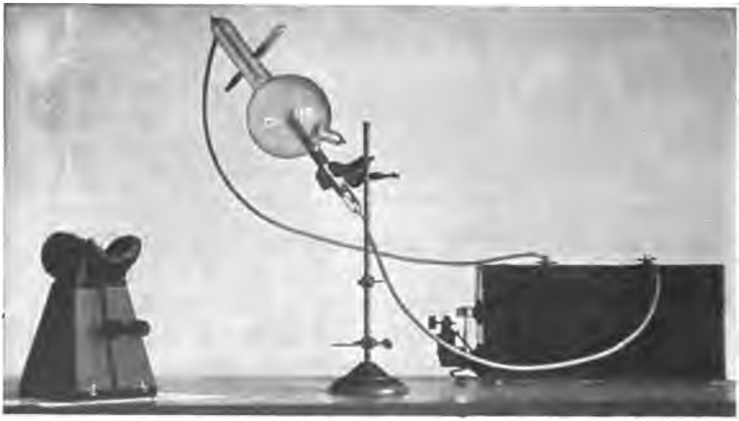
438. The X-Rays.

In 1894 Lenard used a Crookes' tube with a small aluminum window in one side. By directing the cathode rays against this window, he was able to bring them out into the air, for aluminum is much more transparent to the rays than glass is. He showed that the rays would affect a photographic plate and that photographs of objects could be taken by them. Not photographs in fact, but shadows where the object prevented the passage of the rays to the plate.

In 1896 Röntgen discovered the X-rays. He was experimenting with a Crookes' tube in which the vacuum was very high. The tube was all glass—that is, it had no aluminum window. He found that a certain ray, which he called the X-ray, issued from the glass at the points which were bombarded by the cathode particles within the tube. These X-rays are not visible but they are detected by the fluorescence which they cause in certain substances, such as barium platino-cyanide or calcium tungstate.

The X-rays possess a remarkable power of penetrating bodies of matter. They are only slightly obstructed by thick pieces of wood or other substances whose density is small.

FIG. 361.



An X-ray outfit.

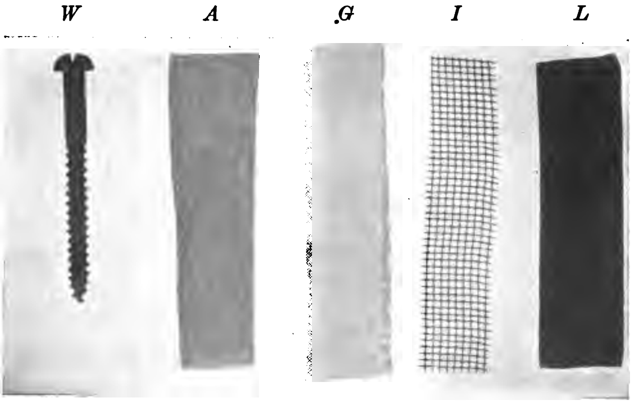
In Fig. 361 is shown an X-ray tube connected to an induction coil. The current enters at the lower electrode. The cathode rays come from the upper electrode and are focused upon a plate of platinum set at an angle of 45° at the center of the tube. The X-rays are reflected by the platinum, causing one-half the bulb to fluoresce.

439. X-Ray Effects.

When X-rays fall upon an ordinary photographic plate, their effect upon the film is the same as that produced by light. That part of the plate upon which the rays fall will turn black when developed. There will be different shades of black, in proportion to the intensity of the rays which reach the plate.

The more dense a body is, the more completely it will stop the passage of the X-rays. In Fig. 362 is shown the *shadowgraph* of several bodies which were placed upon a holder containing a sensitized plate. The X-rays fell upon these objects and passed on through them to the plate in the holder. *W* is wood 2 cm. thick, with an iron screw through its center. *A* is aluminum 3 mm. thick. *G* is glass 1 mm. thick. *I* is a piece of iron-screening. *L* is lead 1 mm. thick. It is observed that the wood stopped but few of the rays, while the screw within the wood is clearly outlined. The aluminum is comparatively thick, but the rays passed freely through it because it is not dense. The glass, while transparent to light, is fairly opaque to these

FIG. 362.

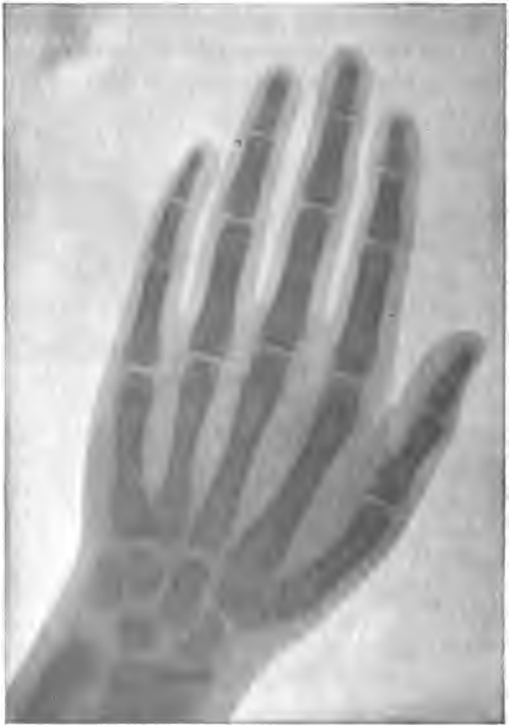


Shadowgraphs of various substances.

rays. The lead, being very dense, almost completely stops the rays.

Since flesh and bone are of different density, the bone being much more dense, it is plain that the method described above may be used to secure outlines of the bones in the living body. The shadowgraph shown in Fig. 363 was obtained by placing the hand upon a plate-holder and directing the X-rays down through the hand to the sensitized plate.

Fig. 363.



X-ray picture of a hand.

This picture is of interest as showing the epiphyses at the joints of a young person.

Any foreign body, such as glass, iron, or lead, which might by accident be embedded in the flesh, could by this means be easily located.

The shadowgraph may be directly observed by looking into a *fluoroscope*. This is a box shaped like that shown in Fig. 361, on the left. The large end is covered with pasteboard, the inner side of which is coated with barium platinocyanide or some other fluorescing substance The observer holds the fluoroscope near the X-ray tube and places his eyes to the small end in such a manner as to exclude light from the outside. Any object placed between the tube and fluoroscope will cast a shadow which may be directly observed upon the screen.

440. Nature of X-Rays.

The rays described above are more properly called Röntgen rays, after the name of their discoverer. Professor Röntgen called them X-rays because their nature was unknown. In that sense they are still X-rays. The most probable theory is that they are not small particles or corpuscles, as the cathode rays are, but waves of ether set up by the impact of cathode particles upon other bodies.

The X-rays travel in straight lines. They cannot be reflected or refracted. A magnet will not deflect them from a straight path.

441. Radio-active Substances.

Certain substances in nature are constantly sending out radiations of various kinds. Radium, uranium, thorium, and others, possess this property. Such substances are said to be *radio-active*, that is, they emit radiations without any apparent cause. The radiations have the power of passing through objects which are opaque to ordinary light, and they continue day and night apparently at a constant rate.

442. The Discovery of Radio-activity.

The discovery of radio-activity was made by M. Henri Becquerel in 1896. He found that a photographic plate was affected by the presence of salts of uranium. The plate was wrapped in black paper so as to completely exclude it from light. Many experiments were tried, all showing that the plate was not affected by any of the ordinary causes. There seemed to be but one conclusion, and that was that the uranium itself was giving off radiations which passed through the black paper and affected the plate.

443. Radium.

The discovery of Becquerel has been followed up by many investigators, most noted among them being M. and Mme. Curie. These two investigators discovered *radium*, a substance which is a million times more active than uranium. The radium which they extracted was found in the mineral pitchblende. By chemical analysis and other forms of separation, a very small quantity of radium is extracted from tons of the pitchblende, about $\frac{1}{100}$ g. from a ton of the mineral.

444. The Rays from Radio-active Substances.

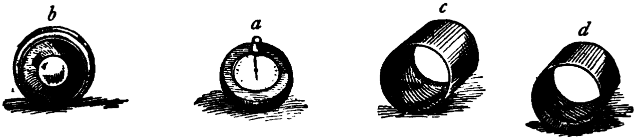
Three distinct kinds of rays emanate from most of the radio-active substances. They are named from the first three letters of the Greek alphabet, the *alpha*, *beta* and *gamma rays*. Some of the prominent characteristics of each are here given.

445. Alpha Rays.

The alpha rays are small particles which are charged with positive electricity. The speed of their motion is nearly one-tenth the velocity of light. They are readily absorbed, and so do not usually proceed far from their source.

An effect of the alpha rays may be observed in a *spinthariscope.* This is a very interesting little instrument devised by Sir William Crookes. It consists of the various parts shown in Fig. 364. The essential part of this instrument (*a* in the figure) consists of crystals of zinc sulphide (the white in the figure) above which is a slender brass hand which has been dipped in a solution of radium or other radio-active substance. Numerous alpha particles fly from the brass hand and strike the zinc sulphide. At each stroke a tiny flash of light can be seen. The ceaseless shower of particles and the resulting flashes of light produce a most interesting and wonderful sight.

FIG. 364.



Parts of the spinthariscope.

The phenomenon is observed through a magnifying glass, *b*. *c* and *d* are tubes which slide one within the other and to which the other parts are attached.

446. Beta Rays.

Beta rays consist of minute particles, or corpuscles, which carry a negative charge of electricity. They move with a velocity nearly equal to that of light. They are deflected by a magnet. Their power of penetration is a hundred times greater than that of the alpha rays.

They will affect a photographic plate and cause barium platino-cyanide to fluoresce.

Thus there appears to be a close resemblance between the beta rays of radium and the cathode rays of the Crookes' tube.

447. Gamma Rays.

Along with the alpha and beta rays are also found what are called the gamma rays. Radium, uranium, and thorium are three radio-active substances each of which give out all three kinds of rays at the same time.

The gamma rays are noted for their wonderful power of penetration. A sheet of lead 1 cm. thick will stop the passage of all beta and alpha rays, but the gamma rays can be detected after passing through several centimeters of lead or thirty centimeters of solid iron.

The nature of the gamma rays is not well known. They do not appear to be charged particles like the alpha and beta rays, for they cannot be deflected by a magnet. They have some properties similar to those of X-rays and are probably a form of ether waves.

448. The Electron.

It appears from the evidence just given, that while matter is composed of molecules and molecules are composed of atoms, the atom itself is composed of a large number of very small particles called *electrons.* The electrons within the atom are in rapid motion relative to each other or possibly in rapid revolution about some point of attraction. The atom may not inaptly be compared to the solar system where the planets revolve about the central sun.

In radium and like kinds of matter the condition within the atom is not a stable one. The atom is disintegrating, or breaking down. The particles of which they are composed retain their motion and fly off with great speed, giving rise to alpha, beta, and gamma rays.

A great mass of experimental evidence is being collected in regard to this new theory of matter. In course of time the true will be sifted from the false and another great step in physical science will have been made.

SUBJECTS FOR BIOGRAPHICAL STUDY.

These names may be assigned to students from time to time for full investigation and report.

1. Archimedes.
2. Francis Bacon.
3. Alhazen.
4. Sir Humphrey Davy.
5. Sir Isaac Newton.
6. Robert Hooke.
7. Count Rumford.
8. Galileo.
9. Pascal.
10. Torricelli.
11. Robert Boyle.
12. Jacques Alexander Charles.
13. Otto von Guericke.
14. James Prescott Joule.
15. James Watt.
16. Christian Huygens.
17. Helmholtz.
18. William Gilbert.
19. Alesandro Volta.
20. Luigi Galvani.
21. Georg Simon Ohm.
22. André Marie Ampère.
23. Coulomb.
24. Michael Faraday.
25. Benjamin Franklin.
26. Joseph Henry.
27. Antoine César Becquerel.
28. Henri Becquerel.
29. Heinrich Hertz.
30. Heinrich Lenz.
31. Sir Wm. Crookes.
32. Sir Wm. Thomson (Lord Kelvin).
33. S. F. B. Morse.
34. Alexander Graham Bell.
35. Thomas Edison.
36. Professor Röntgen.
37. Mme Curie.
38. Sir Charles Wheatstone.

APPENDIX

I.

EQUIVALENT VALUES.

1 meter = 39.37 inches.
1 inch = 2.54 centimeters.
1 foot = 30.48 centimeters.
1 centimeter = .3937 inch.
1 kilometer = .62138 mile.
1 mile = 1.60931 kilometers.
1 liter = 1.7608 pints.
1 gallon = 3.785 liters = 231 cubic inches.
1 gallon = 8.3389 pounds of water.
1 fluid ounce = 29.57 cubic centimeters.
1 gram = 15.4323 grains.
1 kilogram = 2.2046 ($2\frac{1}{5}$ nearly) pounds avoirdupois.
1 ounce avoirdupois = 28.349 grams.
1 pound " = 453.59 grams = $\frac{5}{11}$ kilograms, nearly.

II.

UNITS OF FORCE.

$$\left.\begin{array}{l}\text{dyne}\\\text{poundal}\end{array}\right\}\text{absolute.}$$

$$\left.\begin{array}{l}\text{gram}\\\text{pound}\end{array}\right\}\text{gravitational.}$$

1 gram = 980 dynes.
1 pound = 32.2 poundals.
1 poundal = 13825 dynes.

III.

ACCELERATION DUE TO GRAVITY, IN CENTIMETERS PER SECOND.

Boston	980.395	Philadelphia	980.195
Chicago	980.277	San Francisco	979.964
Cleveland	980.240	St. Louis	980.000

Cincinnati	980.000	Washington	980.111
Denver	979.608	London	981.201
New Orleans	979.323	Spitzbergen	983.08
New York	980.266	At equator	978.07

IV.

UNITS OF ENERGY AND WORK.

GRAVITATIONAL UNITS.

Gram-centimeter = force of 1 g. acting through distance of 1 cm.
Kilogram-meter = force of 1 kg. acting through distance of 1 m.
Foot-pound = force of 1 pound acting through distance of 1 foot.

ABSOLUTE UNITS.

Erg = 1 dyne acting through distance of 1 cm.
Foot-poundal = 1 poundal acting through distance of 1 foot.
32.2 foot-poundals = 1 foot-pound.
980 ergs = 1 gram-centimeter.
100,000 gram centimeters = 1 kilogram-meter.
1 foot-pound = 13,550,000 ergs.
1 kilogram-meter = 7.233 foot-pounds.
1 horse-power = 33,000 foot-pounds per minute.

V.

SPECIFIC GRAVITY OF VARIOUS SUBSTANCES.

SOLIDS.			
Aluminum	2.6	Iron, cast	7.4
Brass (about)	8.5	" wrought	7.8
Beeswax	.96	" steel	7.8
Brick	2.1	Ivory	1.9
Copper	8.9	Lead	11.3
Cork	.24	Nickel	8.9
Diamond	3.5	Oak (about)	.8
Glass, common	2.6	Pine (about)	.5
" flint	3.6	Platinum	21.5
Gold	19.3	Quartz	2.65
Hard Rubber	1.15	Silver	10.5
Ice	.9167	Tin	7.3
		Zinc	7.15

Liquids.

Alcohol	.8
Carbon bisulphide	1.29
Olive oil	.92
Petroleum	.88
Mercury	13.6
Sulphuric acid	1.84
Water at 4° C.	1
Sea water at 0° C.	1.026

Gases (water being 1).

Dry air	.001293
Carbon dioxide	.00197
Hydrogen	.0000897
Nitrogen	.001251
Oxygen	.00143

VI.

AVERAGE COEFFICIENTS OF LINEAR EXPANSION.

Brass	.000019	Silver	.000019
Copper	.000017	Steel	.000011
Glass	.000008	Tin	.000023
Iron	.000012	Zinc	.000029
Platinum	.000009		

COEFFICIENTS OF CUBICAL EXPANSION OF LIQUIDS.

Alcohol	.0011	Mercury	.00018018
Water	.00018		

COEFFICIENT OF CUBICAL EXPANSION OF GASES.

$\frac{1}{273}$ or .00367

VII.

SPECIFIC HEAT.

Air (at constant pressure)	.2374	Lead	.0315
Aluminum	.2122	Marble	.216
Brass	.0939	Mercury (liquid)	.0333
Copper	.0950	Nickel	.1092
Glass	.198	Platinum	.0324
Gold	.0324	Silver	.0599
Hydrogen (constant pressure)	3.409	Steam (constant pressure)	.4805
Ice	.504	Steel	.118
Iron	.1124	Tin	.0559
		Zinc	.0935

VIII.

LATENT HEAT OF FUSION.

Ice	80.	Platinum	27.
Cast iron	23.	Silver	21.
Lead	5.4	Tin	14.3
Mercury	2.8	Zinc	28.

LATENT HEAT OF VAPORIZATION.

Alcohol	202.4	Turpentine	74
Ether	90.	Water	536
Mercury	62.		

IX.

MELTING POINTS IN DEGREES CENTIGRADE.

Aluminum	800	Mercury	—39
Brass	1015	Nickel	1450
Copper	1054	Platinum	1775
Gold	1045	Silver	954
Ice	0	Steel	1350
Iridium	1950	Sulphur	115
Iron, cast	1200	Tin	233
Iron, wrought	1800	Zinc	433
Lead	326		

X.

BOILING POINTS IN DEGREES CENTIGRADE UNDER A PRESSURE OF 76 CM. MERCURY.

Alcohol	78	Nitrogen	—194
Ammonia	—38.5	Oxygen	—184
Benzine	80	Sulphur	446
Carbon dioxide	—78	Sulphuric acid	338
Hydrogen	—243	Turpentine	159
Ether	34	Zinc	950
Mercury	350	Water	100

XI.

BOILING POINT OF WATER UNDER PRESSURE OF CENTIMETERS OF MERCURY, AS SHOWN BY THE BAROMETER.

P = pressure.   B. P. = boiling point.

P.	B. P.	P.	B. P.	P.	B. P.	P.	B. P.	P.	B. P.	P.	B. P.
72.	98.49° C.	73.	98.88	74.	99.26	75.	99.63	76.	100.	77.	100.37
72.1	98.53	73.1	98.92	74.1	99.29	75.1	99.67	76.1	100.04	77.1	100.40
72.2	98.57	73.2	98.95	74.2	99.33	75.2	99.70	76.2	100.07	77.2	100.44
72.3	98.61	73.3	98.99	74.3	99.37	75.3	99.74	76.3	100.11	77.3	100.48
72.4	98.65	73.4	99.03	74.4	99.41	75.4	99.78	76.4	100.15	77.4	100.51
72.5	98.69	73.5	99.07	74.5	99.44	75.5	99.82	76.5	100.18	77.5	100.55
72.6	98.72	73.6	99.10	74.6	99.48	75.6	99.85	76.6	100.22	77.6	100.58
72.7	98.76	73.7	99.14	74.7	99.52	75.7	99.89	76.7	100.26	77.7	100.62
72.8	98.80	73.8	99.18	74.8	99.55	75.8	99.93	76.8	100.29	77.8	100.66
72.9	98.84	73.9	99.22	74.9	99.59	75.9	99.96	76.9	100.33	77.9	100.69

XII.

RELATIVE HUMIDITY.

In this table *t* = temperature of the air, *d* = the dew point, and *t* — *d* would then equal the difference of these two temperatures. The numbers at the head of the columns are the temperatures at dew point, expressed in Centigrade degrees. The numbers in the columns are the humidity. For example, if the difference between the temperature of the air and the dew point is 10° C., and the dew point is 20° C., then the humidity is 55 per cent.

t — d	0	5	10	15	20	25
0	100	100	100	100	100	100
1	93	93	94	94	94	94
2	87	87	88	88	88	89
3	81	81	82	83	83	84
4	75	76	77	78	78	79
5	70	71	72	73	74	75
6	66	67	68	69	70	70
7	61	62	63	65	66	67
8	57	58	60	61	62	63
9	53	55	56	57	58	60
10	50	51	53	54	55	56
12	44	45	47	48	49	50
14	38	40	41	43	44	45
16	34	35	37	38	39	
18	30	31	33	34	35	
20	26	28	29	30	32	
25	19	21	22	23		

XIII.

APPROXIMATE BREAKING-STRENGTH OF WIRES IN KG. PER SQUARE MM.

Brass	60
Copper	40
Iron wire	63
Steel	83

XIV.

COPPER WIRE DRAWN TO THE BROWN AND SHARP (B. & S.) GAUGE.

No.	Diameter in *mm.*	Diameter in *mils*	Resistance in *ohms* per 1000 feet at 60° Fah.	Safe carrying capacity in *amperes* Rubber insulation
0000	11.73	460	.0481	210
000	10.455	410	.06056	177
00	9.31	365	.0764	150
0	8.287	325	.0964	127
1	7.348	289	.1219	107
2	6.544	258	.1529	90
3	5.827	229	.1941	76
4	5.189	204	.2446	65
5	4.621	182	.3074	54
6	4.115	162	.3879	46
7	3.656	144	.491	
8	3.264	128	.6214	33
9	2.906	114	.7834	
10	2.582	102	.9785	24
11	2.305	91	1.229	
12	2.053	81	1.552	17
13	1.828	72	1.964	
14	1.628	64	2.485	12
15	1.459	57	3.133	
16	1.291	51	3.914	6
17	1.150	45	5.028	
18	1.024	40	6.363	3
19	.912	36	7.855	
20	.812	32	9.942	
21	.723	28.5	12.53	
22	.644	25.3	15.9	
23	.573	22.6	19.93	
24	.511	20.1	25.2	
25	.455	17.9	31.77	
26	.405	15.9	40.27	
27	.361	14.2	50.49	
28	.321	12.6	64.13	
29	.286	11.3	79.73	
30	.255	10.0	101.8	

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